NBS-GCR-80-250

Sound Transmission Through Building Structures - Review and Recommendations for Research

Ben H. Sharp
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Prepared for

**Center for Building Technology
National Engineering Laboratory
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TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

LIST OF FIGURES (Continued)

1.0 INTRODUCTORY SUMMARY

The average person spends a major part of his life inside buildings. The home, the workplace, and places for recreation, all provide protection so that we can pursue activities without distraction from the outside world. Such distractions may be in the form of inclement weather or temperature extremes, over which we have no control, and air quality and noise, factors that affect our quality of life and which are technically controllable. The costs of providing this protection have risen rapidly in recent years, yet building attributes, such as acoustical privacy, have become increasingly important as the noise from both outdoor and indoor sources has been rising.

Although the noise levels experienced inside buildings, other than manufacturing plants, are generally not sufficiently high to cause direct physiological damage, such as hearing impairment, there are other undesirable effects. The most obvious effect of noise is to interfere with speech communication. This is serious at school, particularly when students have a language problem or slight (and undiagnosed) hearing impairment. It is also annoying to people engaged in debate or listening to music. Noise also interferes with sleep, interrupting the body's restorative processes, and hence even at moderate levels is considered a health hazard. Finally, the presence of noise reduces the accuracy of work, and sometimes also the quantity of work, particularly when performing complex or demanding tasks. Thus we can see that excessive noise in buildings is not only undesirable, but is potentially harmful to learning and productivity in general.

National programs for controlling noise have been directed mainly towards mitigation of noise at the source, although there are instances where noise control in buildings has been included. This is unfortunate because a virtually complete solution of noise problems in buildings is technically feasible using available methods and is fully compatible with the requirements for cost and energy conservation. This is not to say that the state-of-the-art in building noise control is satisfactory. On the contrary, there are many areas that need further research and development. For example, additional knowledge is required to increase the accuracy and utility of measurement and prediction procedures, so that the cost of noise control can be reduced. Also, we need to explore new types of construction so as to take full advantage of the synergy between sound isolation and energy conservation. Research in these and other areas has declined markedly in recent years, with the result that the

techniques we use today are no different than those of two decades ago. European countries, on the other hand, have successfully used their national laboratories to identify noise problems in buildings and to conduct research programs, so that they have been constantly updating their technology. Unfortunately, this technology is not always compatible with construction practices in the United States.

The purpose of this report is to present a critical review on the status of technology in sound transmission through building structures, and to identify specific areas for further research. The approach taken in the review follows the steps involved in the design process, namely, prediction, measurement, and evaluation, as outlined below.

The multiple requirements of cost, energy conservation, and noise control make it necessary to continually review building construction methods and incorporate the latest advances in technology, emphasizing the many areas of compatibility. Accurate methods of noise prediction allow the engineer and the designer to evaluate the benefits of technological advances, and to optimize designs to satisfy non-acoustical requirements. Before new designs are installed, they must be tested to verify the performance characteristics and to make a realistic comparison with other designs. These tests must be conducted in the laboratory so that the test conditions can be standardized. The field performance will certainly be different from that measured in the laboratory, and the architect will need to know what differences can be expected under various conditions. Hence the need for field measurements, using a procedure that accommodates the widely varying conditions encountered in buildings, and prediction procedures to account for the difference in performance resulting from the varying conditions. With this information available, the architect can design a building for noise control. The final step is to evaluate the effectiveness of the overall design by on-site measurements. For routine evaluation, a simple, quick procedure is required. If the design fails to provide the necessary acoustical conditions, diagnostic techniques are needed to identify the problem areas.

Each of the areas described above are reviewed in this report. Priorities for research are based on the potential for achieving the following objectives:

- To develop new technology to reduce the cost of noise control in buildings;
- To increase confidence that designs will provide the required acoustical privacy;
- To identify and apply sound isolation techniques that reduce energy consumption.

The results of this review are summarized in the following recommendations for research:

1. A study of sound fields in rooms to quantify and develop methods for measuring the degree of sound diffusion. The application of this work is to improve the theoretical representation of real sound fields in prediction methods for transmission loss, understand the effects of sound diffusion on transmission loss, develop performance standards for laboratory test facilities, and relate data measured in the laboratory to that obtained in the field.

2. A parallel project to that of Item #1 to develop a method for measuring room absorption in field situations where diffuse sound fields do not exist, and to utilize this method in the normalization of measured field transmission loss and noise reduction.

3. A study to improve theoretical predictions and procedures for measuring structure-borne flanking transmission in buildings. Existing theories need to be extended for more general application to the type of constructions common to buildings in the United States, and simplified prediction methods developed for use in building design. In great demand is a simple method for diagnosing and quantifying structure-borne flanking in buildings as an alternative to the existing, time-consuming ASTM procedure.

4. A measurement method for the noise reduction of building facades is needed to eliminate the use of individual techniques. The existing ISO and the draft ASTM procedures are not generally applicable to all situations, and include a variety of measurement locations and source types with no guidance on their interrelationship.

5. A national program should be considered for soundproofing buildings in high noise areas to complement government noise source regulations and to reduce energy consumption. The technology for such a program is well known and has been demonstrated, but the costs by region need to be evaluated.

6. A study to categorize subjective reactions to noise in buildings and to relate these reactions to acoustical and building parameters. The results should be

used to develop a model building code based on acoustical privacy, containing realistic provisions for enforcement and for ensuring quality control in construction.

7. Further theoretical and experimental studies are required to extend the theory for double-panel structures to more complex designs. In addition, further development of laminated panels is required, together with a better understanding of thick panels, to reduce the weight and cost of achieving certain STC specifications.

8. A series of studies are needed to examine, both theoretically and experimentally, ways of reducing the cost of achieving the required transmission loss and decreasing the thermal transmittance of certain double-panel structures by modifying the panel-frame connections. New designs for building elements showing an increased benefit/cost ratio have been demonstrated. These designs need to be further developed and tested for fire retardance, flammability, etc. This development should be promoted in the interest of reducing the cost of providing acoustical privacy and reducing energy consumption in buildings after air infiltration paths have been treated.

9. Guidelines are needed to optimize the design of building elements, and combinations of elements, for noise control and thermal transmittance. The data base necessary for the optimization is available in a convenient and compatible form for both quantities.

2.0 TRANSMISSION LOSS OF BUILDING ELEMENTS

The mechanisms of sound transmission through materials and the prediction of the transmission loss of building elements are fundamental to the design of buildings that provide a satisfactory noise environment for the occupants. In this chapter, prediction methods will be discussed for individual elements, such as walls, floors, ceilings, etc., without any consideration for the interaction between different elements that occurs in field installations. The sound-transmitting properties for any given excitation are then a function only of the structural parameters of the element. The application of these prediction methods to buildings will be discussed in a later chapter.

2.1 Transmission of Sound Through Single Panels

The simplest type of structure to consider is a single panel whose thickness is small compared to the associated airborne and structure-borne wavelengths. If the panel is infinite in size, i.e., the dimensions are much greater than the wavelength of bending waves, it can be shown by classical methods[1] that the transmission coefficient τ_θ, defined as the ratio of transmitted to incident sound power, for sound waves incident at single angle θ, is given by the expression:

$$\tau_\theta = \left| 1 + Z \cos \theta / 2\rho c \right|^{-2} \tag{1}$$

where

$$Z = i\omega m - i\omega^3 B (1 + i\eta) \sin^4 \theta / c^4 \tag{2}$$

and ω is the circular frequency ($=2\pi f$), m is the mass of the panel per unit area, ρc is the characteristic impedance of air, B is the bending stiffness of the panel, η is the panel loss factor, c is the speed of sound in air, and $i = \sqrt{-1}$. The corresponding transmission loss TL of the panel at this angle of incidence is given as $TL_\theta = 10 \log (1/\tau_\theta)$.

At low frequencies, Equation (2) is dominated by the inertial impedance 'ωm', giving the familiar mass law where the transmission loss increases at a rate of 6 dB per octave. At high frequencies, the bending stiffness term dominates. At some intermediate frequency, the mass and bending stiffness terms are equal in magnitude and opposite in sign, so that in the absence of damping, the panel impedance Z is zero. The frequency at which this

occurs is termed the coincidence frequency. The lowest coincidence frequency occurs at grazing incidence ($\theta = \pi/2$), and is known as the critical frequency f_c given by the expression:

$$f_c = (c^2/2\pi)\ (m/B)^{\frac{1}{2}} \tag{3}$$

To determine the transmission coefficient for excitation by a reverberant sound field, it is generally assumed that all angles of incidence are equally probable (i.e., the sound field is diffuse – see Chapter 3) and that the average value of the coefficient is given by integrating τ_θ, multiplied by an appropriate weighting factor, over all angles in the range 0 to $\pi/2$. However, at frequencies less than f_c, the value of the transmission loss obtained in this way is found to be from 3 to 5 dB lower than measured values* with the panel installed in the dividing wall between two reverberant rooms.[2,3] The agreement between the calculated and measured results can be improved by arbitrarily limiting the integration range from 0 to θ_ℓ ($\theta_\ell < \pi/2$) where θ_ℓ is chosen simply on the basis that the agreement is good. It is found that different laboratories require different values of θ_ℓ for the calculated results to agree with those measured in the laboratory. The values of θ_ℓ used by various workers ranges from 78° up to 85°.[4] The explanation that is usually given to justify this empirical correction is that the sound field in a reverberation chamber is not totally diffuse and that little sound energy is incident to the panel at grazing angles of incidence. However, there appears to be no experimental justification for this assumption.

At frequencies greater than f_c, the transmission loss is given by the expression:[1,5]

$$TL = 20 \log (m f) + 10 \log (\eta f/f_c) + 10 \log (1 - f_c/f) - 44.5\ ,\ \text{dB} \tag{4}$$

where η is the panel loss factor, and the mass m is expressed in kg/m^2.

The transmission loss of a single panel has been formulated by deBruijn[3] in an alternative way by representing the incident sound field in terms of the spatial cross-correlation coefficient. For a perfectly diffuse sound field, the coefficient is known, and deBruijn shows that the calculated values of transmission loss for a large panel agree well with those obtained using Cremer's theory[1] with integration over the range 0 to 90°. By measuring the cross-correlation coefficient of the sound field in the test laboratory,

* Methods of measuring transmission loss are discussed in Chapter 3.

good agreement is obtained with measured values of transmission loss – see Figure 1. This demonstrates that the theory is correct, but that the simple representation of the sound field as perfectly diffuse is not adequate. Perfectly diffuse sound fields do not exist in the vicinity of test panels in laboratory facilities.

To investigate the effect of sound field diffusion on the transmission loss of a single large panel, deBruijn used fictitious values of the spatial cross-correlation coefficient that might occur in laboratories. The results are shown in Figure 2. At frequencies above f_c, the difference in the three curves shown is small, indicating that sound field diffusion is not important in this frequency region. Below f_c, the difference is up to 5 dB.

The theories developed by Cremer[1] and deBruijn[3] are applicable to very large, or infinite panels excited by an unbounded sound field. Sewell[6] has used classical methods to develop an expression for the transmission loss of a finite single panel excited by a similar sound field. His results show reasonably good agreement with measurements in one test facility – see Figure 3 – without the need to limit the integration over angle to an arbitrary value θ_ℓ. It is stated that the reason for the better agreement with measured results is because finite panels radiate less efficiently at high angles. Sewell demonstrates that the transmission at frequencies less than f_c is dominated by forced or non-resonant motion of the panel, provided that the edges of the panel are free. Clamping the panel can decrease the transmission loss by about 6 dB due to the increased transmission by resonant panel motion.

Josse and Lamure[7] have developed an expression for the transmission loss of a panel between two reverberation chambers by evaluating the coupling between the sound fields in both chambers and the wall. In this case, the panel is finite and the sound field is bounded. At frequencies less than the critical frequency, the major portion of the sound energy is transmitted by forced vibration of the panel, as opposed to resonant vibration, and, according to Josse and Lamure, the major transmission is from sound energy that is incident at small angles to the normal of the panel. The final expression is in good agreement with values measured in several laboratories,[4,8] and is equivalent to assuming a value of about 80° for θ_ℓ in the integration of Equation (1). The transmission loss at frequencies below f_c is given by:

$$TL = 20 \log (m f) - 48 \ , \ \text{dB} \quad (f < f_c) \tag{5}$$

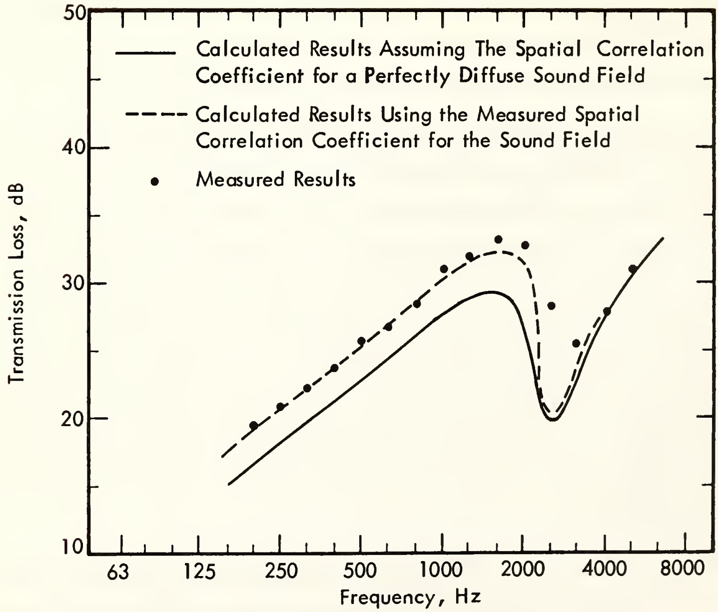

Figure 1. Calculated and Measured Transmission Loss for 1/2-Inch Gypsumboard Panel.[3]

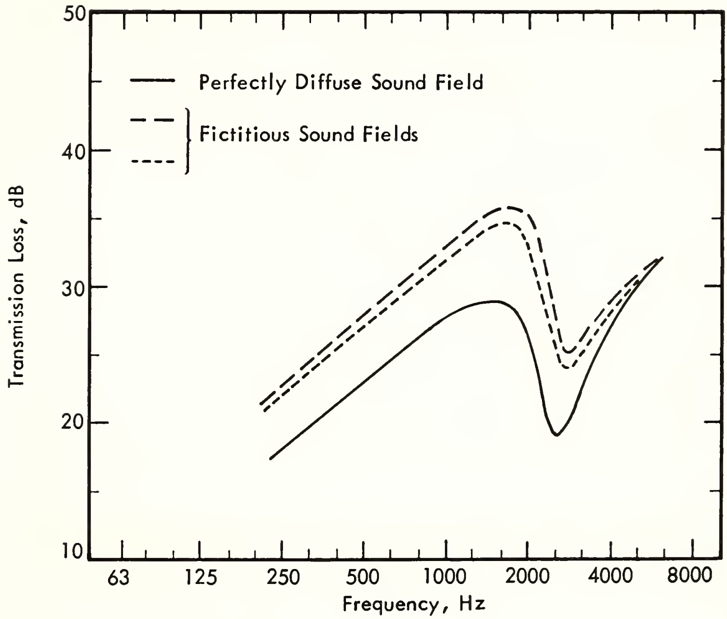

Figure 2. Calculated Transmission Loss for 1/2-Inch Gypsumboard For Various Degrees of Sound Field Diffusion Defined in Terms of the Spatial Correlation Coefficient.[3]

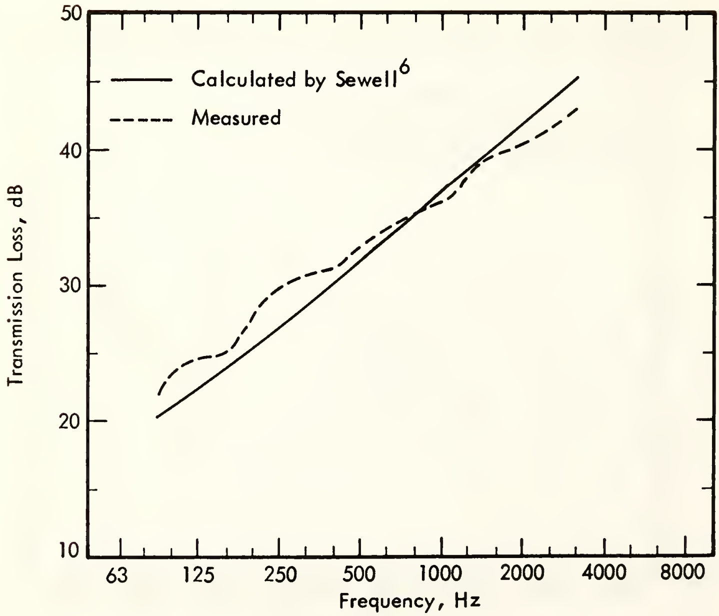

Figure 3. Calculated and Measured Transmission Loss For a Lead Panel.[6]

where the panel mass m is in kg/m^2. Above f_c, Josse and Lamure develop an expression which agrees with that obtained by Cremer[1] and Sewell.[6]

Similar conditions have been examined by Sewell[9] who considers the transmission of sound through a single panel in a waveguide. At frequequencies greater than f_c, he finds good agreement with infinite panel theory, i.e., Equation (4). Below f_c, resonant transmission is 3 dB greater than for a panel in an infinite baffle if panel losses are low, and 6 dB greater if the losses are high. Forced transmission in the frequency range is the same as the integration of Equation (1) over the angular range 0 to $\pi/2$. Therefore, regardless of whether resonant or forced transmission dominates, the transmission loss for a panel forming the entire wall between reverberant rooms is less than if it is placed in a baffle between the rooms. As will be discussed later in Chapter 3, this result is significant in the design of laboratory test facilities.

Finally, Nilsson[10] has developed expressions for the transmission loss of a single panel forming the common wall between two rooms. His estimation of the effect of panel boundary conditions are similar to Sewell's for an unbounded sound field.[5] At frequencies greater than f_c, he shows that panel boundary conditions are unimportant, and that the transmission loss agrees within 1 or 2 dB with that given in Equation (4). Below f_c, Nilsson's expression for transmission loss is within 1 dB of that obtained by Josse and Lamure[7] in Equation (5). In this frequency range, Nilsson also includes factors related to the room absorption to account for non-diffuse sound fields.

Using Equations (4) and (5), it has been shown[8] that the available theory agrees well with measured values for simple panels in one laboratory facility – see Figure 4. The problem is that different measured results are obtained in different facilities (more on this in Chapter 3). Since deBruijn has shown[3] that good agreement can be obtained by carefully measuring the sound field characteristics and inserting them into the theoretical expressions, it is clear that all current theories suffer from an inadequate, generalized representation of the incident sound field. In the discussions that follow, the expressions given for the transmission loss of building elements are those that agree with the average of measured results taken in various test facilities.

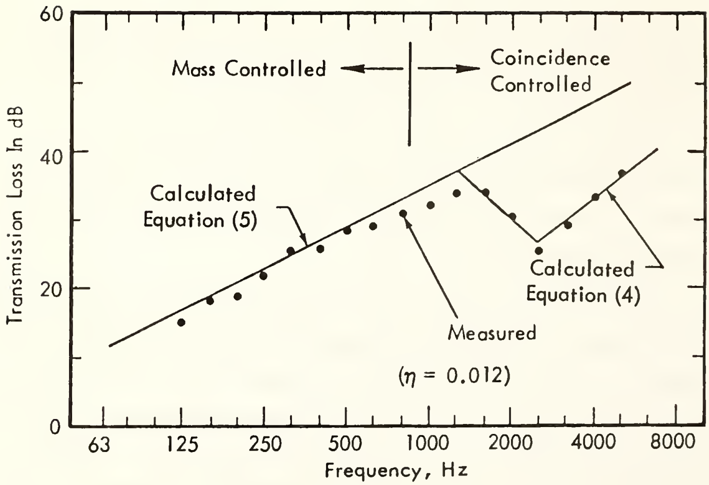

Figure 4. Measured and Calculated Values of the Transmission Loss of 1.59 cm (5/8-inch) Gypsumboard.[8]

2.2 Corrections For Panel Thickness

If the thickness of the panel is not small compared to the wavelength, then the assumptions made in the derivation of the expression for the impedance, Z, of the panel are not valid. Cremer[11,12] shows that this occurs when the bending wavelength is less than 6 times the panel thickness. The type of wave motion that is predominant in the panel at any given frequency is the one that presents the lowest impedance to the applied sound field. Examination of the panel impedance, as given by Equation (2), shows that the term representing the bending wave impedance assumes high values at high frequencies. Therefore, as the frequency is increased, it becomes more probable that the wave motion will change from pure bending to some other type that presents a lower impedance.

This change in the wave type is predicted by the theory for thick panels[8,13] which provides for a more exact representation of the panel motion than does the simple theory for thin panels. The theory shows that a change from bending to shearing waves occurs in a frequency range determined by the physical properties and thickness of the panel. Within this frequency range, the overall impedance of the panel changes from one dominated by the bending impedance to one in which the shearing impedance is of prime importance.

For the majority of lightweight building materials, such as gypsumboard, plywood, etc., the change in wave type occurs at such a high frequency that the effect is of minor concern. When it comes to considering more massive materials (concrete is a good example), the change in wave type may occur at frequencies well within the frequency range of interest, resulting in a significant reduction of the transmission loss. The effect is shown clearly in Figure 5 for a 15 cm concrete panel. The theory for thick panels gives good agreement with measured results for the 15 cm concrete panel, except in the vicinity of the critical frequency, whereas the application of the theory for thin panels gives results that are substantially in error. The effect of shear is represented by the difference between the two predicted curves and results in the concrete panel exhibiting a transmission loss approximately 6 dB less than the calculated mass law at frequencies greater than the critical frequency. This reduction of 6 dB is common to the majority of concrete and brick structures, and can be taken into account at frequencies above coincidence by assuming the effective mass of the panel is one-half that of the actual mass. The result is that concrete and brick structures provide lower values of transmission loss than would be expected for their mass, a fact that is well known from field and laboratory measurements.[14,15]

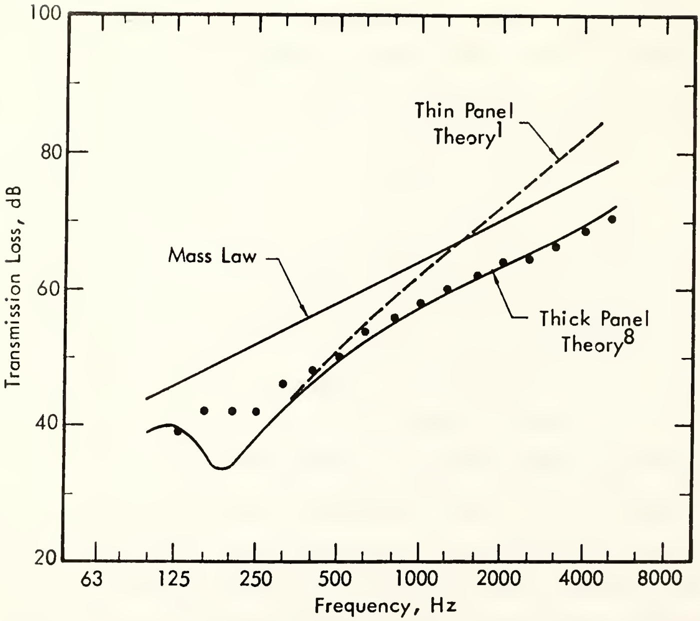

Figure 5. The Measured Values of Transmission Loss for a 15 cm Concrete Panel Compared to Values Predicted by Means of the Thin and Thick Panel Theories.[8]

2.3 Multi-Layer Panels

To a large extent, the transmission loss of a single panel is determined by its mass; the greater the mass, or the thicker the panel, the greater the transmission loss, except at frequencies near the critical frequency where the characteristic dip in transmission loss curve is exhibited. Below the critical frequency, the maximum achievable transmission loss is given by the mass law. Above the critical frequency, theory shows that values greater than those given by the mass law can be achieved, unless the panel thickness is sufficiently great for shearing to occur — see Section 2.2. Since the value of the critical frequency is inversely proportional to the panel thickness, any attempt to increase the transmission loss by increasing the thickness automatically lowers the critical frequency, perhaps into a frequency region of major importance. Multi-layer panels offer the possibility of a transmission loss greater than that given by the mass law by designing for a very low value of the critical frequency. Alternatively, they allow for an increase in panel mass without a corresponding decrease in critical frequency.

For a multi-layer panel consisting of two or more individual thin panels rigidly connected at the interface, the bending stiffness can be calculated from the results of Oberst[16] or Kerwin, et al.[17] This value can then be inserted into Equation (1), and integrated over angle θ to determine the transmission loss. This is the approach taken by Cremer and V.Meier[18] and Holmer[19] with fairly good results in some cases. Alternatively, the wave equation for the multi-layer panel can be solved directly with the appropriate forcing function to determine the transmission coefficient τ_θ which is then integrated over angle θ. This approach is taken by V.Meier,[20] Sharp and Beachamp,[21] Ford, et al.,[22] with mixed results.

In general, attempts to achieve in practice a multi-layer panel with high stiffness to take advantage of the increased transmission loss above the critical frequency have not been successful. The most popular method has been to use a honeycomb core, exhibiting high shear stiffness, sandwiched between two thin panels. The problem with this construction is that core materials with a sufficiently high shear stiffness are difficult to find and expensive to produce.[20] As the bending stiffness of the overall structure is increased so as to reduce the critical frequency, the preferred wave motion in the panel changes from bending to shearing (see Section 2.2).

In contrast, attempts to increase the panel mass without increasing its stiffness have been successful. Two methods have been demonstrated for achieving this objective. The first may be termed "mass-loading", and involves the addition of discrete masses to a flexible panel with a high critical frequency.[23,8] If the masses are separated by a distance less than the bending wavelength, the construction will exhibit a critical frequency identical to that of the flexible panel, but with a greatly increased total mass. An example of the acoustical performance of such a panel is shown in Figure 6.[8] The construction in this case is a 0.32 cm fiberglass panel loaded to a mass of 19.5 kg/m^2 with small squares of a mixture of sand and vibration damping compound (the latter used merely to hold the sand in place; containing the sand in egg cartons would be preferable, but was difficult to manufacture). The reduction in transmission loss at the high frequencies indicates that the base panel was stiffened somewhat by the addition of the sand mixture, but the principle of mass-loading is demonstrated. An alternative method of mass-loading, and one that is easier to manufacture, is to apply a flexible sheet of a heavy material to a base panel. The application of lead in this way has been demonstrated by Cremer and V. Meier.[18] An example of adding asphalt roofing paper to a plywood panel is shown in Figure 7.[8]

The second method of increasing panel mass without increasing its stiffness is by means of a 3-layer construction, the center layer selected so that the bending stiffness is high at low frequencies but low at high frequencies.[24] In this way, the structure can provide the stiffness necessary to withstand lateral, zero-frequency loads, yet exhibit a high critical frequency. The center layer may be an adhesive material used to join the two outer panels. The characteristics of the structure are then determined by the properties of the adhesive. It is possible to remove this dependence by "spot" laminating, whereby the adhesive is applied in small discrete amounts on a square lattice over the surface of the panels.[8] The two panels then effectively decouple and behave more or less independently at a frequency determined mainly by the spacing of the adhesive spots. An example of the acoustical performance of such a construction is given in Figure 8, showing that the transmission loss can be increased by increasing the mass without moving the dip occurring at the critical frequency to lower frequencies. This type of multi-layer panel has significant advantages over single panels in the design of building elements exhibiting high transmission loss.[8] It remains to be shown that it satisfies the requirements of local building codes, and can be installed with no added difficulties.

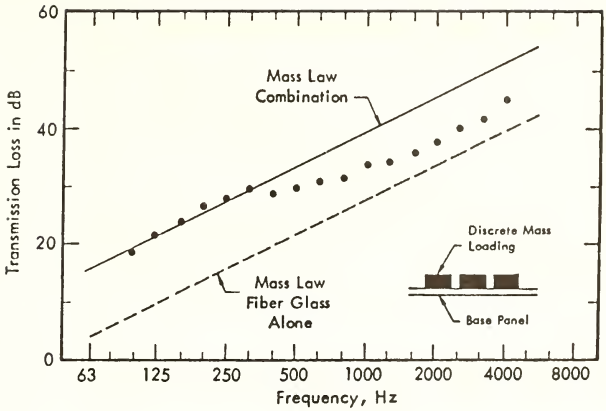

Figure 6. Measured Values of the Transmission Loss of a 0.32 cm Fiberglass Panel Mass Loaded to 19.5 kg/m^2 With Sand.[8]

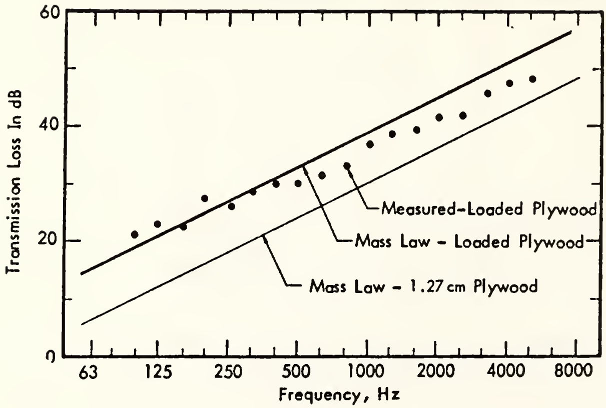

Figure 7. Measured Values of the Transmission Loss of a 1.27 cm Plywood Panel Mass Loaded to 19.5 kg/m^2 With Asphalt Roofing Paper.[8]

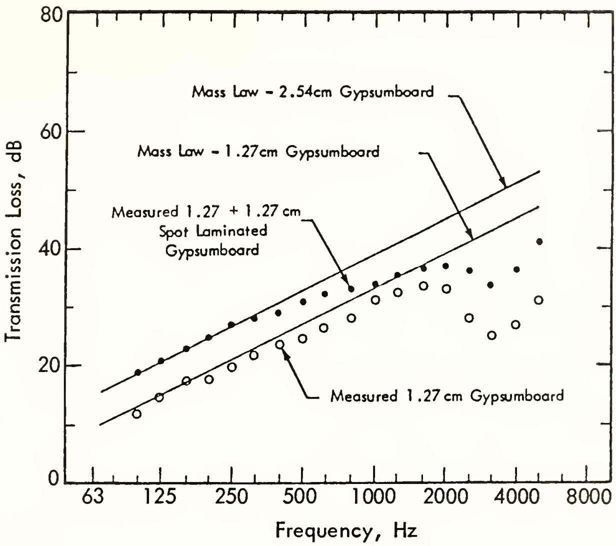

Figure 8. The Measured Values of Transmission Loss for a Single and Two 1.27 cm Spot Laminated Sheets of Gypsumboard.[8]

2.4 Double-Panel Constructions

One method of obtaining higher values of transmission loss than that available from a single panel is by the introduction of one or more additional panels with intervening air spaces. The multiple-panel construction formed in this way is naturally more complex to analyze than the corresponding case for a single panel, because the transmission loss is dependent on a greater number of construction parameters. Expressions for the transmission loss of a double-panel construction of infinite lateral extent have been derived by Hurst[25] for normal incidence, and by London,[26] Josse,[27] and Mulholland, et al.,[28] for random incidence. Sewell[29] has developed a solution for a finite double panel in an infinite baffle. In most cases, problems have been encountered in accounting for absorption in the cavity. London[26] obtains agreement between theory and measurement by postulating a resistive term in the panel impedances, although there is no experimental evidence for such a term. Mulholland, et al.,[28] use simple ray theory and some arbitrary assumptions on cavity absorption to obtain satisfactory agreement. Cummings and Mulholland[30] obtain reasonable agreement by assuming that absorption occurs only at the cavity edges. Sewell's approach for finite double panels assumes that the cavity edges are completely open, i.e., the absorption coefficient is unity.

In each case, reasonable agreement is obtained between measurements and theory, but the expressions are very cumbersome. Sharp[8] has shown that, if there is absorption in the cavity, the transmission loss of a double panel with no interconnections between the panels can be approximated by the expressions:

$$TL = \begin{cases} TL_M & f < f_o \\ TL_{m_1} + TL_{m_2} + 20 \log (fd) - 29 & f_o < f < f_\ell \\ TL_{m_1} + TL_{m_2} + 6 & f > f_\ell \end{cases} \qquad (6)$$

where TL_M, TL_{m_1}, and TL_{m_2} are the values of the mass law transmission loss calculated from Equation (5) for the total construction ($M = m_1 + m_2$), panel 1 ($= m_1$) and panel 2 ($= m_2$), respectively. The quantity f_o is given by $113/\sqrt{m_e d}$, where m_e is equal to $2m_1 m_2/(m_1 + m_2)$, and represents the frequency at which the fundamental mass-spring-mass resonance of the panel masses and the cavity air stiffness occurs. The

quantity d is the separation of the two panels in meters, and f_ℓ is equal to (55/d) Hz. The transmission loss calculated by these expressions is in good agreement with measured values at frequencies less than the critical frequency of either panel, as shown in Figure 9 for two panels that obey the mass law over the entire frequency range of interest. If the critical frequency of the panels lies within the frequency range of interest, then Equation (6) also applies, provided that the values of TL_M, TL_{m_1}, and TL_{m_2} are taken as measured or calculated values of transmission loss for the individual panels, including the effects of coincidence — see Figure 10.

The presence of absorption in the cavity has been found to be important in achieving high values of transmission loss for double-panel constructions with no interconnections between the panels.[8,31,32] It has been demonstrated[8] that the effect of the absorption is to reduce the amplitude of lateral standing waves in the cavity that effectively couple the two panels at the antinodes. In the absence of absorption, this coupling is so strong that the transmission loss is little better than that given by the mass law — see Figure 11 — thus explaining some of the results obtained by London.[26] It is interesting to note the increase in transmission loss at low frequencies — a result that is contrary to common opinion. In the context of meeting STC requirements (see Section 3.3), this is an important result since the STC of double-wall constructions is often determined by the transmission loss values at low frequencies.

In practice, of course, the transmission loss of double-wall constructions at any given frequency has an upper limit that is determined by the type and number of mechanical connections between the two walls. As a result, the usefulness of absorption material in single-stud walls is debatable, and should be considered on a case-by-case basis using available methods of prediction. However, the upper limit introduced by connections usually occurs at a frequency which is a few one-third octaves greater than the fundamental mass-spring-mass resonant frequency of the double wall. The addition of absorption material apparently can increase the transmission loss at these frequencies, and hence should be considered as a useful addition.

In other forms of double-wall construction that incorporate framing consisting of staggered studs, split studs, or double studs, or where the walls are resiliently mounted to the studs, the addition of absorption material in the cavity can result in a significant increase in transmission loss — on the order of 3 to 8 dB depending largely on the wall construction.

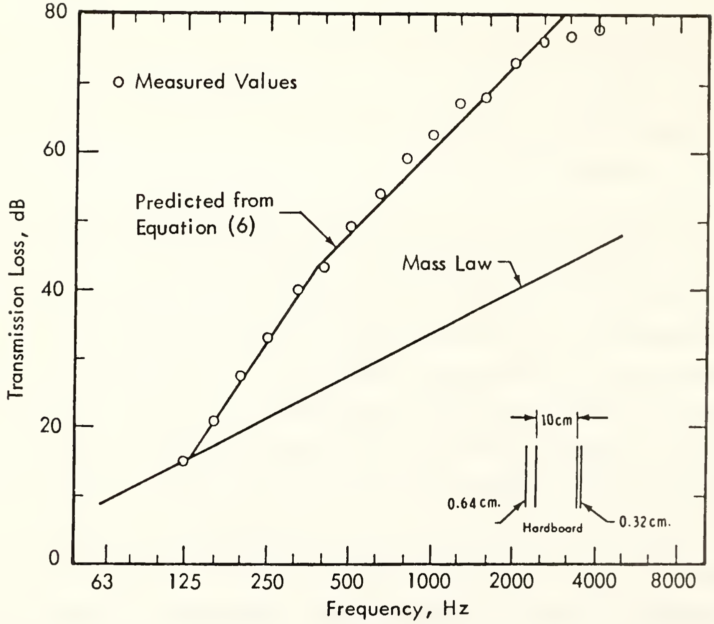

Figure 9. Measured Values of the Transmission Loss of a Double Panel Compared to Values Calculated by the Approximate Method. Fiberglass Batts in the Cavity for Measured Data.[8]

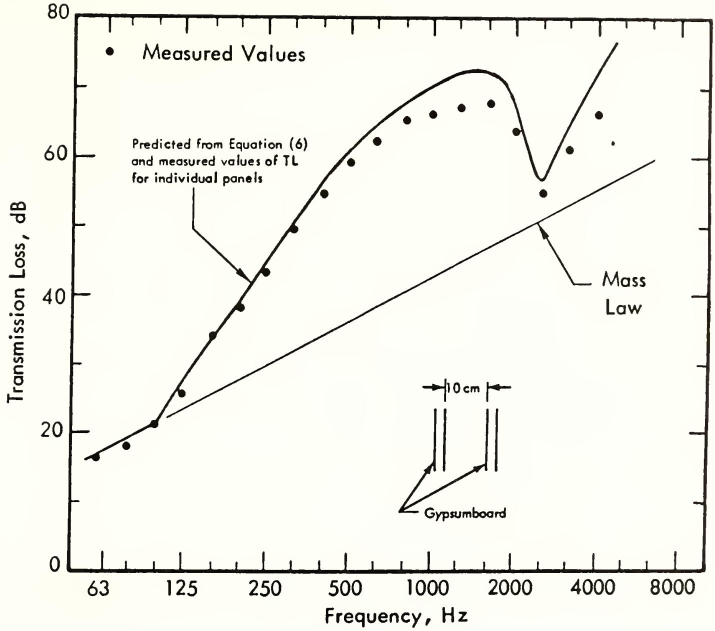

Figure 10. Measured and Calculated Values of the Transmission Loss of 1.59 cm (5/8-inch) Gypsumboard. Fiberglass Batts in the Cavity For Measured Data.[8]

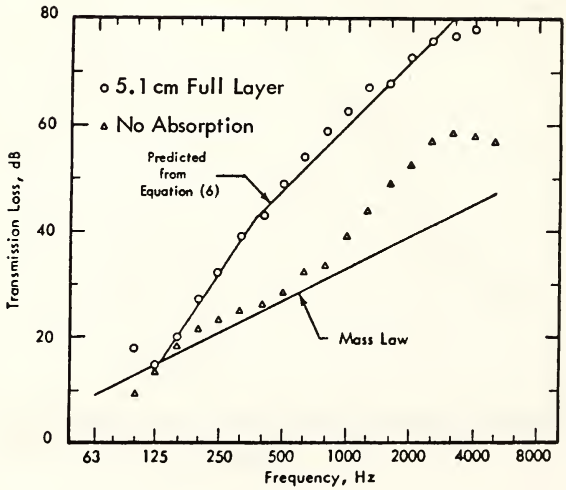

Figure 11. Measured Values of the Transmission Loss of an Isolated Double-Wall Construction With and Without Cavity Absorption. The Construction Consists of 0.64 cm and 0.32 cm Hardboard With a Spacing of 16 cm.[8]

One of the major assumptions in the previous discussion of double-panel structures is that the two individual panels are completely isolated from one another. This means that the only path of energy transfer between the two panels is an airborne path. In practice, it is necessary to have some form of connection between the panels to provide the added stiffness for the construction to withstand lateral loads. These connections usually take the form of wooden or metal studs in building structures and metal ribs and stringers in aerospace structures. Their effect is to provide an additional transmission path in parallel to the airborne path previously considered, with the result that acoustic radiation from the structure is increased and the transmission loss correspondingly reduced. It is not usually possible to eliminate these interpanel connections, or "sound bridges" as they are called, and so it is necessary in the design of multiple-panel structures to be able to determine the effect that they have on the transmission loss.

Fahy[33] has studied the propagation of waves in frame walls, and has developed generalized expressions[34] for panel displacement coefficients and acoustic coupling factors that can be used in analyses similar to those for sound transmission through single panels. No experimental data are given to validate the theory. Zabarov[35] has obtained expressions for the transmission of sound through double walls joined at the edges showing reasonably good agreement with measured results conducted on one-fifth-scale plywood models. He shows that longitudinal wave motion in the panels must be considered together with flexural motion if the edge connections are very stiff. Simple expressions are given to predict the increase in transmission loss over that provided by a single wall. Lin and Garrelick[36] have also formulated solutions for the transmission of sound through an infinite double panel with periodically spaced, rigid frames. Absorption is not included in the cavity, so the numerical results show a considerable number of resonances that are not apparent in measured results. However, the formulation is useful as it allows determination of the relative strengths of structure-borne and airborne transmission.

More recently, Sharp[8,37] has made use of relationships developed by Heckl[38] for calculating the sound power radiated by panels excited by line and point forces to derive simple expressions for the transmission loss of double panels with line stud and point connections. The general form of the transmission loss for mass-controlled panels as a function of frequency is shown by the dashed line in Figure 12, where it can be seen that the values

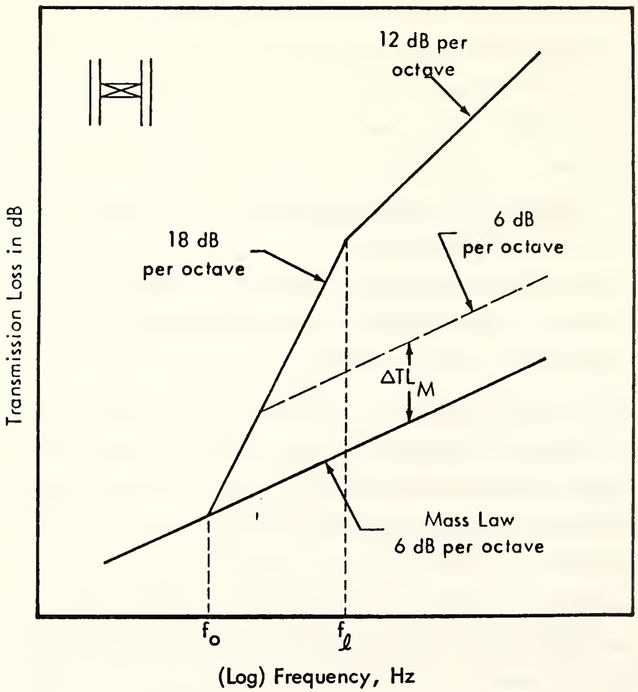

Figure 12. General Form For the Transmission Loss of a Double Panel With Sound Bridges.[8]

at medium and high frequencies are a constant ΔTL_M greater than the mass law for the total structure. In the simplest case where the two panels are identical, the expressions for ΔTL_M are as follows:

<u>For Line Connections, i.e., Studs:</u>

$$\Delta TL_M = 10 \log (bf_c) - 24 \quad , \quad dB \qquad (7)$$

where b is the stud spacing in m.

<u>For Point Connections:</u>

$$\Delta TL_M = 20 \log (ef_c) - 51 \quad , \quad dB \qquad (8)$$

where e is the spacing of the connections, assumed to be on a square lattice, in m. Expressions for other configurations are given in References 8 and 37.

The agreement of this prediction method with measured results is good at frequencies less than the critical frequency – see Figure 13. Better agreement at the critical frequency can be obtained using measured or calculated transmission loss values for each panel including the coincidence effect. The value of the quantity ΔTL_M can be increased by 5 to 10 dB by changing from line (stud) connections to point connections — see Figure 14 — particularly if one of the panels has a high critical frequency. The use of laminated panels for this purpose is demonstrated in Reference 8, where the calculated and measured transmission loss are presented for a series of experimental and practical prototype constructions covering a wide range of STC values. Figure 15 shows that the transmission loss of these new constructions is significantly greater than that for existing constructions of equal total mass.[8] This is particularly true at the higher masses where existing masonry and concrete structures tend to perform poorly in relation to their mass. The approximate in-place costs (in 1972 dollars) of the new constructions are shown in Figure 16 together with costs for existing constructions calculated by the same method. It is noticeable that there is a significant reduction in cost for constructions with an STC rating greater than 45.

The transmission loss of double panels with studs can be increased by inserting resilient materials between the panels and the studs. For a common gypsumboard wall with wooden studs, the transmission loss is increased by up to 10 dB at medium and high

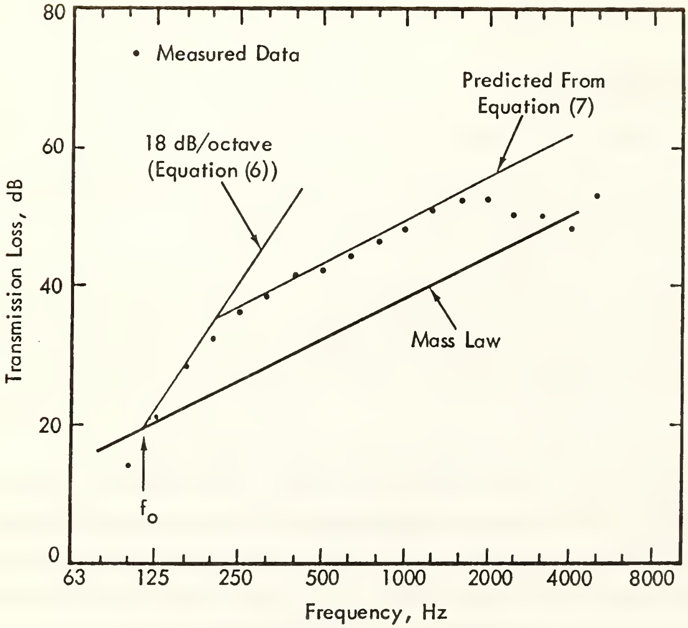

Figure 13. Measured and Predicted Transmission Loss For a Double-Panel Construction of 1.59 cm and 0.95 cm Gypsumboard With Wooden Line Studs 0.61m on Center and Fiberglass Batts In the Cavity.[8]

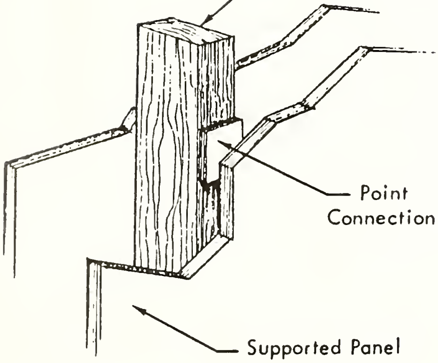

Figure 14. Method of Providing a Point Connection to One Panel In a Double-Panel Construction.

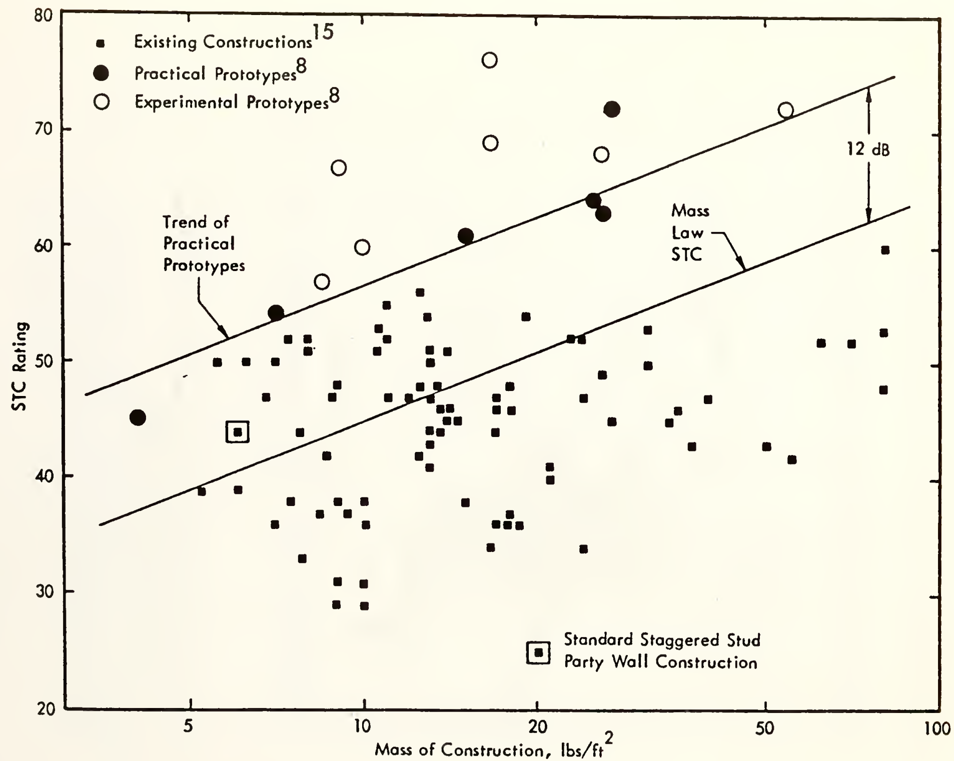

Figure 15. The STC Rating as a Function of the Mass For Existing[15] and Prototype[8] Wall Constructions.

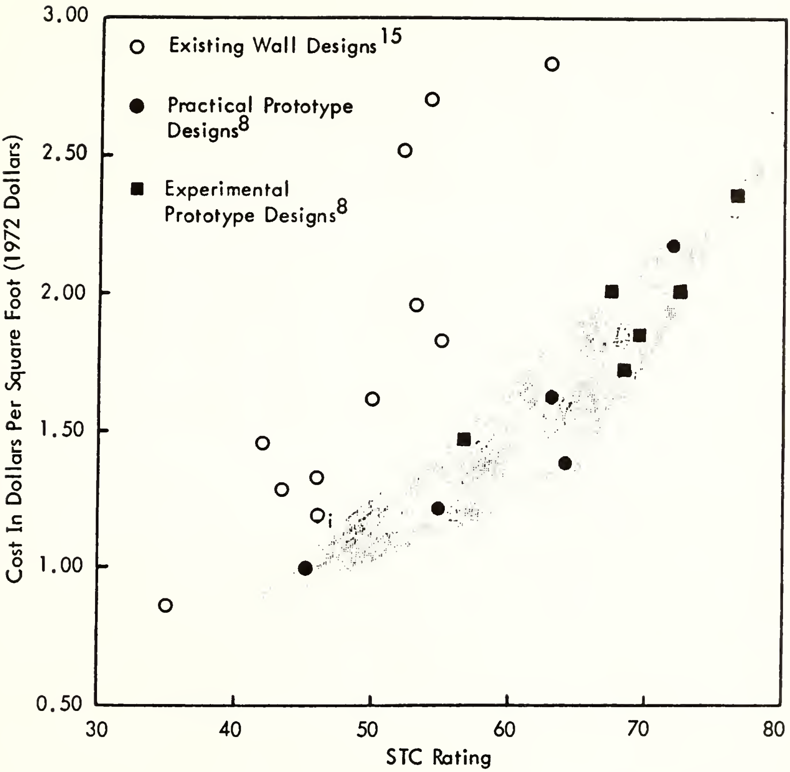

Figure 16. Cost Versus STC Rating For Existing[15] and New Wall Designs.[8]

frequencies.[8] This increase is greater than that obtained by substituting resilient metal studs for the wooden studs, and the structure retains its load-bearing capabilities. Inserting resilient materials between panels and point studs can result in an increase of up to 5 dB at medium and high frequencies.[8]

The results presented in Reference 8 show that building elements can be designed to provide high transmission loss without the need for massive and costly masonry and concrete panels. Conversely, it is possible to achieve a performance equal to that of existing structures, but at reduced mass and cost. Using the data in Figures 15 and 16 as a rough indicator, it appears possible to achieve STC ratings in the range 45 to 60 at a weight reduction of 20 percent and a cost reduction of 30 to 35 percent relative to existing structures that have been typically used over the last 20 years.

It has been shown by Cremer,[18] Sharp,[8] and Reinicke[39] that certain multi-layer constructions can perform more like double panels and provide values of transmission loss in excess of the mass law. This performance can be achieved using a three-layer construction where the center layer is porous. Further improvements are possible if the center layer is porous and massive.

2.5 Summary and Recommendations

The theories for sound transmission through single panels are well established, with the exception that existing methods for representing the incident sound field are inadequate. Current prediction methods incorporate an empirical adjustment factor to account for the lack of understanding of the sound field, this factor being specific to the laboratory in which the basic theory is verified. As will be shown in the following chapter, measurements performed on nominally identical structures in different laboratories can vary by 5 to 10 dB at some frequencies. This introduces major problems in attempts to validate new theories of sound transmission for more complex structures. Furthermore, it complicates the application of measured data and existing theories to field application, where completely different sound fields are encountered. Some approaches to gain a better understanding of sound field characteristics are given in Chapter 3. Finally, it should be noted that an error of only 3 dB in the prediction of transmission loss can result in the specification of a panel that is 40 percent too heavy.

Prediction methods are also available for thick panels and laminated structures of simple design, although further work is required to understand, and perhaps make use of, shearing effects. Since the current trend in buildings is away from the use of massive brick and concrete structures, further research on thick panels may not be a high priority. Laminated structures, however, have a large application in the design of double-panel constructions, and should be developed further. Specifically, it is necessary to examine proposed concepts and designs, understand their characteristics more fully, and develop a range of optimum parameters for particular applications. Existing simple theories can serve as a good basis for this work.

Double-panel constructions provide the increased transmission loss necessary to ensure acoustical privacy in buildings, relying on the performance of the two individual panels and the intervening air space. In the absence of any connections between the two panels, the transmission loss can be accurately predicted, In the more usual case, with connections via wooden or steel studs and edge frames, prediction methods are reasonably good at frequencies below the critical frequency, but only fair at higher frequencies. The prediction methods described in this chapter are applicable to all building elements, including windows, if the type of connection can be defined simply, or if the vibration transmission through the connection is known. To date, the theory has been applied to fairly simple structures only. Further work is required to extend it to more complex structures, and to account for more complex connections. For example, the application to floor/ceiling assemblies needs to be studied more thoroughly. In addition, design guides similar to those presented in Reference 8 need to be developed to enable the designer to select optimum materials and configurations for a given transmission loss performance.

Initial work on the performance of double-panel constructions with a rigid porous center layer acting as the cavity has shown considerable promise. Such constructions have the potential for achieving STC ratings on the order of 45 at a thickness of only 5 cm. They are thus suitable for internal partitions in offices and for exterior doors, provided that adequate edge seals are included. The theory for this type of structure is in its infancy, and needs to be further developed so that the material parameters can be optimized.

The review of prediction methods in this chapter has shown that there are several new concepts for achieving required values of transmission loss at lower cost and weight

than for typical existing structures. Some of these concepts have been tested and their potential demonstrated in the form of prototype constructions. Yet very few, if any, have found their way into common building practice, perhaps because they are relatively unknown, or because their performance in other areas, such as fire retardation, flammability, and load-bearing capacity, has not been determined. In some cases, changes may be necessary in outdated building codes, to permit constructions to be selected on the basis of performance standards, so that new designs can be accepted.

To promote this new technology for the building industry, it is first necessary to translate the conceptual designs and experimental prototypes into practical structures. These structures must then be tested to determine compliance with building performance requirements. Finally, the advantages gained by using the new technology must be demonstrated.

3.0 LABORATORY MEASUREMENTS OF TRANSMISSION LOSS

3.1 Philosophy of Laboratory Testing

The sound transmission loss of a structure can be measured by placing it in the dividing wall between two rooms, one of which – the source room – is equipped with a source of sound, and measuring the sound level in each room. The difference in sound levels, when suitably corrected for the area of the structure and the absorption in the receiving room, is then equal to the transmission loss of the structure. The correction, or normalization, is designed to provide values of transmission loss that are independent of the test facility, so that the transmission loss is purely a function of the structural parameters. If the sound field in the source room is diffuse (see Section 3.5.1), then the measured transmission loss should be equal to that predicted by the methods described in Chapter 2, assuming that these methods properly account for all significant structural parameters. Unfortunately, it is difficult to obtain a diffuse sound field at low frequencies unless the rooms are very large, and even the degree of "diffuseness" required has not been established and is even more difficult to measure. Moveover, the way in which the structure is mounted in the dividing wall, together with other factors, can affect the measured values of transmission loss. The result is that the measured values can, and do, depend on the characteristics of the measurement facility.

It can be argued that it does not matter if there is some limited variation between measurements conducted in different facilities, because the acoustic performance of structures in field applications is often completely different to that measured in the laboratory – see Chapter 4. This is often true when careful attention is not given to flanking transmission, air leaks, and good workmanship in the construction. However, poor field performance need not be assumed outright – it indicates that improvements are required in building design, or that our understanding of field structures is incomplete. This approach to laboratory testing tends to discourage the search for improved prediction procedures, and hence makes the design process even more difficult and costly than it is at present.

Another factor that must be considered in this context is the application of laboratory measurements to validate theories of transmission loss. This is, in fact, the only way to test different theories for accuracy. If different facilities provide different values for the same

construction, it is possible to conceive of situations where theories are facility specific! That this actually occurs even with current standard test methods suggests that considerable control is needed in the measurement of transmission loss.

There are two possible approaches to the development of a standard test procedure. The first approach is to attempt to measure the transmission loss of a structure in such a way that the values obtained are independent of the measurement facility and are a function only of the properties of the structure. This method allows direct comparison of the performance of different structures, thus simplifying the architect's job in selecting structures for a given building requirement. The disadvantage is that this type of test provides information as to the potential performance of a structure — a performance that often may not be achieved in the field. This places the burden on the acoustical engineer to develop improved procedures for predicting or improving the field performance of structures.

Since the field performance of a structure is the factor that determines the noise environment in the finished building, the second approach to testing is to simulate field conditions as closely as possible. Then no adjustments to the measured data would be required for it to be used in calculating building sound levels. This approach is not satisfactory because the range of conditions to be simulated is too extensive to be approximated in any one facility. The standard test procedures for measuring transmission loss in the laboratory are therefore designed to minimize the influence of the facility.

3.2 Standard Test Procedures

In the United States, testing is performed according to the ASTM E90-75 procedure.[40] In Europe, the procedure used up until 1978 is defined in the ISO Recommendation R140 (1960)[41] (subsequently replaced in 1978 by ISO Recommendation 140 — see Section 3.6). The basic elements of both these procedures are essentially the same.

The structure to be tested is installed in the common wall between two reverberation rooms designed so that the flanking transmission loss (see Chapter 5) is at least 10dB greater than the transmission loss of the structure at all frequencies. In this regard, it is recommended that the common wall be a double isolated construction with the test structure mounted in the wall of the receiving room. The ASTM procedure recommends room volumes of at least 160m^3 for measurements in the one-third octave band centered on 100 Hz, although in

deference to existing smaller facilities, a room size of $80m^3$ is acceptable but not recommended for new installations. The ISO R140 procedure states that the room volumes should be greater than $50m^3$, with a desirable volume greater than $100m^3$. Thus the ASTM procedure is the stricter of the two and should give more repeatable results at low frequencies. To increase the diffusion of the sound field, the ASTM procedure suggests the use of randomly spaced diffusing elements or rotating reflectors. A minimum dimension of 2.4m is required for the test structure, except for doors and windows, which should be of normal size. Both procedures state that the structure should be installed so that the edge conditions are as similar as possible to normal field installation.

A source of sound, usually one or more loudspeakers emitting white or pink noise, is provided in one of the rooms — the source room — and measurements are taken of the space-time average sound pressure levels $\overline{L_1}$ and $\overline{L_2}$ in the source and receiving rooms using bandwidths of one-third octave in the frequency range 100 or 125 Hz to 4000 Hz. The number of measurements required in the ASTM procedure to sample the sound field in each room is calculated to ensure 95 percent confidence limits of ±3 dB in transmission loss at 125 Hz and 160 Hz, ±2 dB at 200 Hz and 250 Hz, and ±1 dB at higher frequencies. No such requirements are contained in the ISO R140 procedure. The transmission loss, TL, of the test structure is then given by the expression:

$$TL = \overline{L_1} - \overline{L_2} + 10 \log (S/A) \tag{9}$$

where S is the area of the test structure, and A is the absorption in the receiving room. The term 10 log (S/A) is commonly referred to as the normalization factor.

3.3 Single Number Descriptors For Transmission Loss

The methods described above for measuring transmission loss in the laboratory are designed to give detailed data on the acoustical performance of structures as a function of frequency. It is common to present the results in each of 16 or 17 one-third octave bands. This information is valuable to the acoustic specialist so that he can fully understand the change in performance with frequency and can perform detailed calculations on the expected sound isolation in finished buildings. However, the data in this form are often confusing to the non-acoustical specialist, such as the architect who has the task of designing the building,

and the official responsible for checking compliance with local building codes. Furthermore, the amount of data presented makes it difficult to rank-order structures and assess their suitability for specific applications. To simplify the design and enforcement tasks, considerable effort has been given to developing single number descriptors of the acoustical performance of structures.

The earliest scheme for describing in a single number the transmission loss properties of a structure was simply to average the values of transmission loss over the frequency range of interest. It was soon discovered that this method was unsatisfactory because the same average number would be given to structures with completely different frequency characteristics. A more suitable method was therefore developed to account for the variation of performance with frequency in a way that is consistent with the requirements for acoustical privacy. This method involves the use of a grading curve, specifying the transmission loss required in each one-third octave band, against which the measured values for a given structure are compared. The grading curve concept can be used in two ways — it can represent a strict requirement for all structures to be used in a given building type, or it can be adjusted to give a ranking of one structure against another. Since it would be unreasonable to discriminate between two structures whose transmission loss characteristics differed by only one or two decibels in a frequency band, current grading procedures allow for a certain number of deviations below the grading curve.

Several different grading curves have been developed or suggested for use in building design. Basically, the curves have been determined by taking the difference between typical source levels in buildings and suitable criteria for acoustical privacy in neighboring rooms. A comprehensive description of the basis for the different grading curves has been prepared by Yaniv and Flynn.[42] In their review, they conclude that the subjective response data used to establish the requirements for sound levels in dwellings is extremely variable and has led to the development of a number of grading curves that differ by up to 10 dB at some frequencies. The lack of a comprehensive data base on subjective response does not allow an assessment to be made of the importance of these differences. Also, the shape of the grading curve for partitions is dependent on the typical source spectrum selected for the calculations. As a result, there is considerable uncertainty as to the validity of current grading procedures.

In the United States, the standard grading procedure for the transmission loss of building structures is given in ASTM E413-73, Standard Classification for Determination of Sound Transmission Class (STC).[43] Initially, this procedure was intended for application to data measured in the laboratory, and thus provided a single number for ranking the potential performance of structures. The same grading curve is also used to describe the field transmission loss of structures (FSTC) and the noise reduction between rooms (NIC — Noise Isolation Class)[44] — see Chapter 4.

3.4 Repeatability of Transmission Loss Measurements

In using the standard procedures for measuring transmission loss, it has been observed that different results can be obtained for nominally identical structures tested in different laboratories. In some cases, the differences have been sufficiently large to cause concern about the test specifications contained in the standard procedures. To determine the magnitude and the extent of the potential inaccuracies for tests conducted in facilities that satisfy the standard requirements, there have been several attempts to obtain inter-facility comparisons under carefully controlled conditions. Three of these comparison tests are described in this section.

Kihlman[45] has reported tests conducted in five facilities in Sweden and Denmark, each one satisfying the requirements specified in ISO R140, that are considered to be typical designs. The source and receiving rooms were identical in size in three of the facilities, in one facility the difference in volume was less than 5 percent (although the width and height were the same for both rooms), and in one facility the difference was about 60 percent. The tests were conducted on two structures, lightweight concrete and chipboard, first mounted firmly in the test aperture, and then supported by a rubber lining around the perimeter. Sound level measurements were taken at 20 positions in each room with diffusers used to increase the diffusion at low frequencies. In addition, the loss factors of the mounted test structures were measured.

The range of measurements in five facilities is shown in Figure 17 for the chipboard panel and in Figure 18 for the lightweight concrete panel. The data in these two figures corresponds to the firm mounting condition. It can be seen that the range of values measured in the different facilities is only about 3 dB above the critical frequency, but

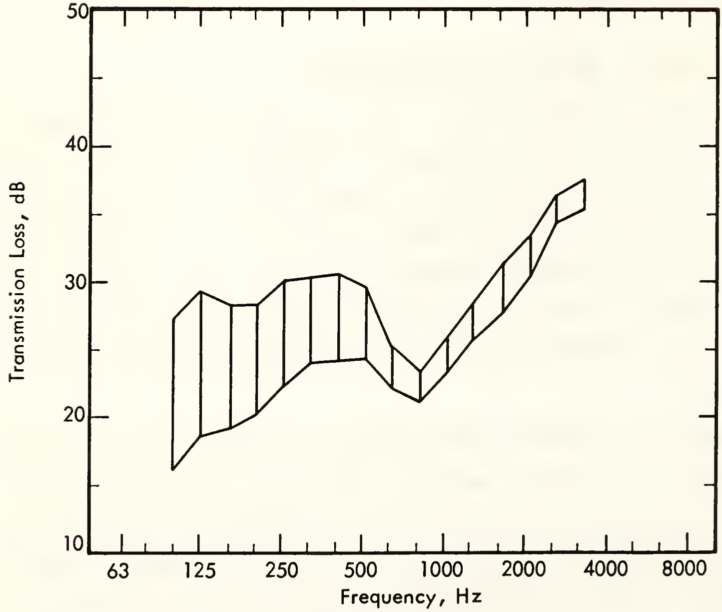

Figure 17. Range of Data Obtained From Measurements on a 5cm Chipboard Panel in Five Test Facilities.[45]

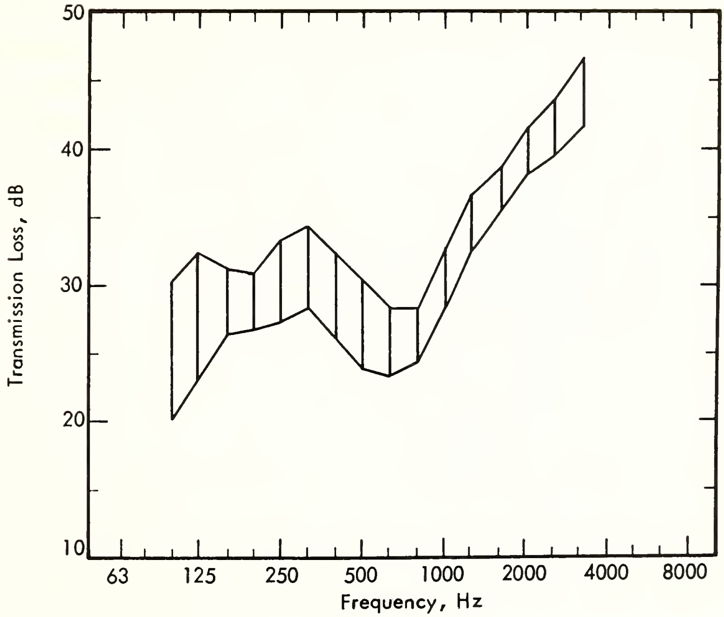

Figure 18. Range of Data Obtained From Measurements on a 7cm Lightweight Concrete Panel in Five Test Facilities.[45]

is as much as 10 dB at lower frequencies, increasing as the frequency decreases. Considering that the tests were well controlled using standard materials, the discrepancies are indeed disturbing.

Higginson[46] describes a series of controlled measurements conducted by twelve different testing organizations on a single structure forming part of a field test facility. The source and receiving rooms were both 42m^3 in volume which is rather small for test laboratories, but according to the requirements of ASTM E90-75, they are acceptable (but not recommended for new installations) for measuring transmission loss at frequencies of 125 Hz and greater. Each of the twelve organizations were first asked to measure the transmission loss of a 23 cm solid brick wall using their own equipment in their normal way. This led to a considerable variation in equipment, sound field sampling, number and type of diffusers, and noise sources. The results of these tests are shown in Figure 19, the spread being 10 dB at frequencies up to 500 Hz, and 3 to 5 dB at higher frequencies.

Jones[4] reports the results of measurements conducted in seven test facilities in the United States. The tests were conducted over a number of years according to different versions of the ASTM procedure (E90-66, E90-70, and E90-75) with gradually stricter requirements for room design and measurement accuracy. Thus the results do not necessarily represent the current state-of-the-art in transmission loss testing. The spread of values obtained on measurements of a 0.16 cm lead vinyl sheet is shown in Figure 20, indicating a range of 7 dB up to 200 Hz, and 3 to 5 dB at higher frequencies. Similar tests conducted on 22-gauge galvanized sheet metal and 1.3 cm gypsumboard panels showed a smaller spread of data on the order of 3 to 5 dB over the frequency range 125 Hz to 4000 Hz. Tests at two facilities on a wood-frame wall with gypsumboard on double-row studs showed a similar difference of between 3 to 5 dB at all frequencies – see Figure 21 – the difference in STC rating being 6 points.

In summary, it appears that measurements of transmission loss conducted in laboratories satisfying the requirements of standard test procedures can vary by as much as 5 to 10 dB at low frequencies and 3 to 5 dB at high frequencies. This range has also been reported by other authors in more limited comparisons of test data.[47,48] These ranges are very approximate, but the information is sufficiently discouraging to warrant further inspection of the standard test procedures.

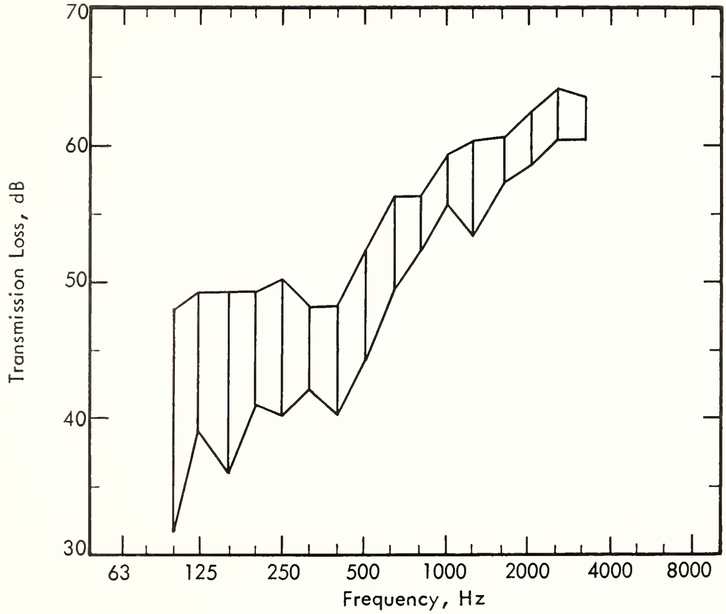

Figure 19. Range of Data Obtained From Measurements on a 23cm Brick Wall By Twelve Organizations in the Same Test Facility.[46]

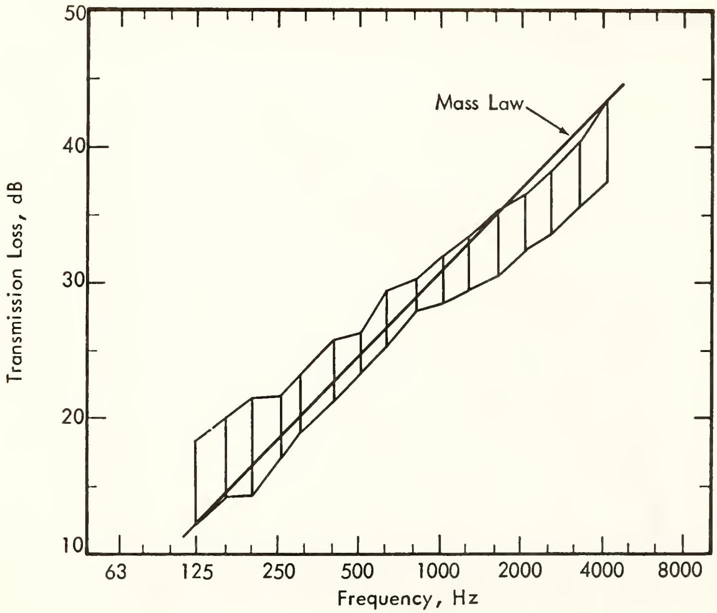

Figure 20. Range of Data Obtained From Measurements on a 0.16cm Lead Vinyl Panel in Seven Test Facilities.[4]

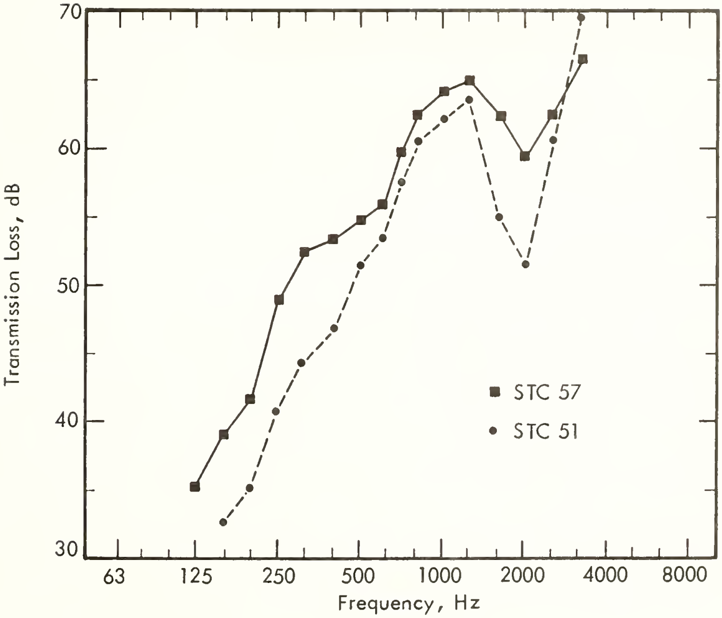

Figure 21. Data Obtained From Measurements on a Wood-Frame Wall With Gypsum Board on Double Row Studs at Two Test Facilities.[4]

The only common feature of the tests described above is that each series was performed using the same, or nominally the same, test structures. All other parameters were allowed to vary. Accordingly, the results by themselves cannot be used to identify the cause of the discrepancies. Fortunately, in two of the series, additional tests were performed with constraints on some of the more important parameters. These tests are described in the following section.

3.5 Factors Influencing Measured Values of Transmission Loss

Several theories have been presented in an attempt to explain the discrepancies between measurements conducted in different laboratories. The factors influencing the measured values are individually discussed in this section and finally summarized to provide a basis for recommending further study.

3.5.1 The Sound Field In The Source Room

It was noted in Chapter 2 that the transmission loss of a structure is a function of the incident sound field, and hence depends on the characteristics of the source and receiving rooms in a laboratory test facility. To obtain agreement with measured data, it is necessary to perform the integration of Equation (1) over the range 0 to θ_{max}, where θ_{max} is different for different laboratories. This does not necessarily mean that no sound is incident at angles greater than θ_{max}. The value of θ_{max} is selected merely to give agreement with the measured results. It has been shown by De Bruijn[3] that good agreement can be obtained between measured and calculated values if the sound field characteristics (specified in terms of the spatial correlation coefficient) are measured and inserted into the theoretical expressions. Sewell's classical approach[6] does not require the assumption of a limiting angle of integration, but provides fairly good agreement with measurements in one facility only. Similarly, the theories of Josse and Lamure,[7] and Nilsson,[10] who consider transmission between two rooms, do not include sufficient descriptions of the sound field to be applicable to different test facilities that are known to give different measured values. Clearly, a better knowledge of the incident sound field is necessary to understand the reasons for interlaboratory differences in measured data.

Sound Field Diffusion

It is common to describe the characteristics of a sound field in terms of its "diffusion", a useful concept if only it could be quantified. As noted by Schultz,[49] "perfect diffusion" can be defined in many alternative ways, some of them seemingly equivalent. Two common definitions are: equal probability of sound propagation in all directions, and uniformity of sound pressure; although it is not at all certain that the two are equivalent. An equal probability of sound propagation in all directions may result in the sound pressure being uniform, but the reverse is not necessarily true. To be consistent with the derivation of the expression for transmission loss, the first definition will be used to describe perfect diffusion (see also Schroeder[50]). This condition can be represented mathematically in terms of a relatively simple expression for the spatial correlation function.[3]

A perfectly diffuse condition can be approached in the laboratory at high frequencies, or if the source and receiving rooms are very large. Practical constraints set a limit to the size of a measurement facility, however, so that it has been necessary to study methods for achieving diffuse sound fields in rooms smaller than desirable.

The angular distribution of sound energy flow in a reverberation room has been measured by Meyer[51] and Venzke and Dammig[52] using a directional microphone array consisting of a group of microphones inserted in parallel, slotted tubes. Using this array, Venzke and Dammig have shown that the angular distribution is far from uniform even at medium and high frequencies. The introduction of diffusing elements was found to improve the uniformity significantly. Unfortunately, this method of measurement is practical only at medium and high frequencies. At low frequencies, where the increased modal frequency separation leads to poor sound diffusion, the dimensions of the directional microphone array become unacceptably large and cumbersome for routine measurements.

Bolt and Roop[53] have suggested tentatively that an estimate of sound diffusion in a room can be obtained by studying the frequency response characteristics obtained with single, fixed loudspeaker and microphone locations. They noted that the value of the "frequency irregularity" per unit bandwidth (a term originally defined by Wente[54] as the sum of the peak levels minus the sum of the minimum levels over a given frequency band in the room frequency response) was consistently lower for a room designed specifically for high sound diffusion than for hard-wall rectangular rooms. However, subsequent studies,

as reviewed by Schultz,[49] have shown theoretically and experimentally that, above a certain frequency, the frequency irregularity is a function of the reverberation time of the room — a quantity that is unrelated to sound diffusion.

The effect of room shape on sound diffusion has been studied by Bolt, et al.,[55] using boundary perturbation theory to extend wave acoustics techniques to non-rectangular rooms. A greater spreading of sound energy, and hence increased sound diffusion, was found by reducing the symmetry of the room and by introducing irregularities at the boundary. The same conclusions have been drawn by Waterhouse[56] in an analysis of data presented by Sato and Koyasu.[57] In a theoretical development, Maa[58] shows that non-uniformity in the angular distribution at a surface in rectangular rooms is caused by modes perpendicular and parallel to the surface. Sepmeyer[59] has calculated the angular and spatial distribution of sound in a reverberant room and has examined in detail the effect of room dimensions. In general, he determined that the distributions are strongly dependent on the room dimension ratios, and that only in very few cases are both uniform spatial and angular distributions found in rooms of any dimension.

Studies on the effect of room perturbations have led to the development of stationary and rotating diffusers that effectively increase the modal density. Actually, the rotating diffuser, which is currently the most popular method for increasing diffusion, does not increase the modal density as such, but increases the number of modes excited over the time period for each rotation. There are no generally accepted methods for quantifying or measuring the degree of diffusion in a room, so that the benefits of rotating diffusers have often been assessed by noting a decrease in the spatial variance of the sound pressure level,[60] which as noted previously is not necessarily a good indicator. Cook, et al.,[61] have demonstrated that perfect diffusion, as defined in terms of the spatial correlation coefficient, is approached by the use of rotating vanes, but they also note that large departures from perfect diffusion may cause only small changes in the coefficient. This insensitivity of the correlation coefficient for measured sound field diffusion has been reported by other workers. One fact is known, however — using rotating diffusers does not provide transmission loss values that agree with the diffuse sound field theory when the integration of Equation (1) is performed over the range 0 to $\pi/2$. Therefore two possibilities arise:

- Rotating diffusers do not provide a sufficiently diffuse sound field when defined as equal probability of sound propagation in all directions;

- A perfectly diffuse sound field may exist in the body of the room, but not at the surface of the test structure.

It has been shown by Furduev,[62] Cook, et al.,[61] and De Bruijn[3] that the spatial cross-correlation coefficient is a useful method for defining sound field diffusion, but that it is rather insensitive to changes in diffusion. Cook suggests that better results could be obtained by measuring the coefficient in three mutually perpendicular directions, but it is not clear how these data would be interpreted or introduced into the theoretical expressions for transmission loss. Balachandran[63] has used the cross-correlation coefficient to compare the efficiency of diffusing elements in producing a perfectly diffuse sound field. He shows that measured absorption coefficients depend on the diffusion up to a point where the standard deviation of the difference between measured and "perfect" values of the correlation coefficients is less than a certain amount. This approach could be applied to transmission loss measurements, and would provide a simple criterion with which to rate facility performance.

An alternative approach to measuring sound diffusion, discussed by Bart,[64] and by Blake and Waterhouse,[65] is to use the imaginary part of the normalized cross-spectral density between the sound pressure at two locations (the cross-correlation coefficient used by Cook, et al., represents the real part). Analysis shows that this function is quite sensitive to sound propagation direction.

Stochastic models of sound fields are normally used to provide statistical measures of the spatial variations of sound pressure in rooms. However, Lubman[66] has demonstrated that directional information can also be obtained from these models. He proposes a method that involves measuring the power spectrum from a microphone moving in a straight line. The traversing microphone spectra provides estimates of the mean square pressure and spatial variation, but also gives an indication of directional diffuseness. For a perfectly diffuse field the spectra is a rectangle, making it easier to distinguish deviations from the ideal condition than is possible for the damped sinusoid function of the cross-correlation coefficient.

Modal Coupling

In measuring the transmission loss of structures, it is often found that the values obtained at low frequencies are greater than would be expected from Equation (1) in Chapter 2. London[67] was one of the first to notice this discrepancy, and proposed the addition of a resistive term to the impedance expression to account for it. Sewell's expression[6] for transmission loss contains terms involving the panel area and shape, and at low frequencies, these terms predict a flattening of the transmission loss curve. From this result, Jones[4] concludes that the flattening of the curve is due to panel size effects. The effect can be explained by considering the coupling of the acoustic modes in the source and receiving rooms with the panel modes of vibration. Kihlman[68] has shown theoretically that, within a limited frequency interval, there are very few acoustic modes that couple strongly with the panel modes. He predicts that the transmission loss of the common wall between two reverberant chambers is greater if the two chambers are dissimilar in shape than if they are identical. Figure 22 shows data measured by Kihlman to support his theory. Note that the measured values obtained with the two dissimilar rooms are essentially the same as those obtained with identical rooms equipped with hanging diffuser panels. To validate the modal coupling concept further, the sound transmission between the same two chambers was arranged to occur through a tube in the common wall, thereby eliminating the coupling to the panel modes. It was then found that changing the dimensions of one of the chambers had a negligible effect on the measured values of transmission loss.

A similar effect has been noted by Schultz[49] in the measurement of transmission loss for a single wall-board panel forming the common wall between two rooms. He found that by moving the panel less than 4 inches, the transmission loss at low frequencies could be increased by up to 3 dB.

Nilsson[10] has shown theoretically that room shape and size has little effect on the transmission loss of a panel if the exciting sound field is diffuse. However, when the field is not diffuse, his theory indicates that it is necessary to take into account the absorption in both the source and receiving rooms.

The coupling of acoustic and panel modes was also well demonstrated in initial tests conducted in the Wyle Research transmission loss testing facility.[69] The two rooms of this

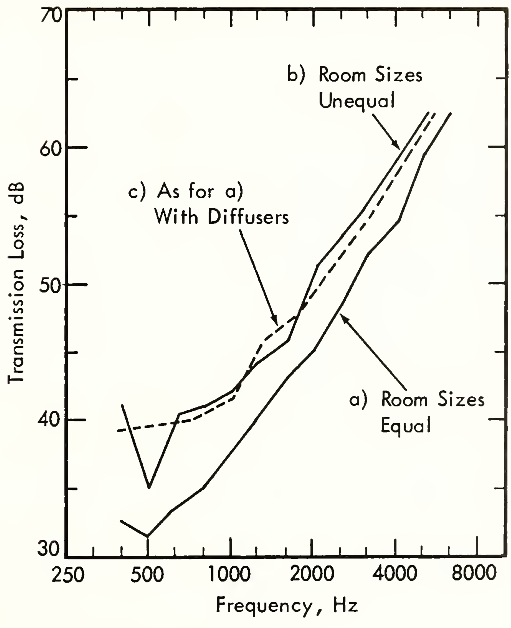

Figure 22. Measured Data for a 3.5cm Concrete Wall Showing the Effect of Room Size and Diffusers.[68]

facility are identical in size and shape, each having a volume of 181 cubic meters. When conducting tests with the rooms empty, the measured values of transmission loss agreed very well with those calculated according to the mass law, even at very low frequencies. In other words, the familiar flattening of the curve was not evident. By introducing five diffuser panels in one of the rooms, the transmission loss measured at low frequencies increased by up to 3 dB. Moreover, the same result was obtained without the diffusers by filling one of the rooms with carbon dioxide to change the modal frequencies without changing the room dimensions or the modal density. In this latter experiment, the measured values at medium and high frequencies remained unchanged.

At higher frequencies where the modal density in the source room is high, the condition of ideal sound field diffusion with an equal probability of propagation in all directions should be approached. Under this condition, the measured transmission loss should agree with the calculated value using a limited angle of incidence of 90°. There is some indication that this occurs in some laboratories with the result that the measured transmission loss increases at a rate of 4 to 5 dB per doubling of frequency rather than the 6 dB per doubling of frequency as predicted by the mass law. Low coupling of the sound field with the test structure at low frequencies together with more perfect diffusion at high frequencies would explain this lower rate of increase with frequency. However, this measured trend in the transmission loss is far from the general rule.

The effect of absorption in one or both of the rooms in a transmission loss facility is to broaden the bandwidth of the acoustic modes. The coupling between the sound field, the test structure, and the acoustic modes in the receiving room is then less critically dependent on slight differences in room dimensions. Kihlman[68] has shown theoretically that the effect of different room sizes on the transmission loss decreases as the room absorption is increased. In field studies, Jones[70] presents data showing that the field transmission loss increases as absorption is added to the source and receiving rooms. These data tend to support the hypothesis that the coupling between room modes plays an important part in determining the measured transmission loss in both laboratory and field tests.

In summary, there is strong evidence to suggest that some of the discrepancies between measurements and calculations are the result of imperfect sound diffusion in the vicinity of the test structure. The theoretical models for sound transmission do not include

a good representation of the exciting sound field obtained in the laboratory. Efforts to improve the sound diffusion are hampered by the lack of a suitable measurement technique. At low frequencies, discrepancies are due to modal coupling effects. In fact, these effects should be expected where the modal density is low and the acoustic wavelength is the same order of magnitude as the panel dimensions. Moreover, the magnitude of the discrepancy will be dependent on the relative dimensions of the two rooms and the location of the panel in the common wall.

3.5.2 Test Structure Mounting

The transmission loss of an infinite panel is dependent on the forced response of the panel – the bending waves being forced by the exciting sound field. In a finite panel, the forced waves are reflected at the perimeter to produce free waves that are in resonance at certain frequencies. Thus the transmission through a finite panel is part forced and part resonant. Below the critical frequency, forced transmission predominates. However, if the edges of the panel are securely clamped, resonant transmission can increase and reduce the overall transmission loss as calculated by the mass law. This effect has been predicted by Nilsson[10] and Sewell.[6] The difference in transmission loss between simply supported and clamped conditions is estimated by Nilsson to be independent of the panel loss factor with a magnitude of about 3 dB at low frequencies, decreasing as the frequency approaches the critical frequency. Sewell's formulation indicates a strong dependence on the panel loss factor, as might be expected since resonant response should decrease with increasing panel damping. Data taken by Kihlman[45] do not necessarily agree with either theory, but do indicate an increase in transmission loss just below the critical frequency for an elastically mounted lightweight concrete panel.

Above the critical frequency, the predicted transmission loss according to Cremer's[1] theory is strongly dependent on the panel damping, but is unaffected by the panel boundary conditions if these are lossless. In practice, edge losses occur at the boundaries due to the type of mounting and to transmission of energy into the surrounding structure. Thus the measured transmission loss is dependent of the coupling between the test panel and the facility structure, the dependence being a function of the properties of the test panel. Measurements conducted on lightweight concrete panels firmly and elastically mounted confirm these findings and show that the differences in transmission loss can be explained by the difference in measured panel loss factors.

3.5.3 Test Structure Size and Location

Theories for sound transmission through finite panels predict a decrease in the transmission loss at low frequencies as the panel size increases. At higher frequencies, but still below the critical frequency, the theories predict a reverse trend with panel size. Thus the slope of the transmission loss curve as a function of frequency may increase as the panel size is increased. Above the critical frequency, there is no dependence on panel size.

If the test panel takes up the entire common wall between the source and receiving rooms, i.e., wall to wall, floor to ceiling, then the coupling of the sound field with the panel may be such as to decrease the transmission loss from the value obtained for a smaller panel mounted in a massive common wall. Kihlman[45] reports data showing a difference of up to 5 dB at low frequencies between the two conditions. To minimize the difference between laboratories and to be more representative of field conditions, Kihlman recommends that laboratory test openings extend the full width and height of the source room. This would normally require either large test panels or small source rooms, although the required condition can be realized if the test rooms are constructed with angled ceilings and splayed walls.

3.5.4 Test Aperture

Holmer[71] has suggested that the lack of diffuseness in the incident sound field is not due to the properties of the source room, but may be the result of localized sound field perturbations at the aperture in which the panel is placed. He specifies the size, shape, and depth of the aperture as parameters influencing the incident sound field, and hypothesizes that irregularities in the transmission loss at certain frequencies are due to aperture resonances.

Kihlman[45] has conducted experiments to demonstrate that the aperture parameters can indeed affect the measured transmission loss of a panel. A single wall of gypsum board was tested in a laboratory facility with and without a simulated aperture on one and on both sides of the wall. The source and receiving rooms in the test facility were of equal size, the depth of the simulated apertures was 1.3m. The results of the experiment are shown in Figure 23. Note that the values of transmission loss without apertures and with apertures on both sides of the wall are essentially the same, except at very low frequencies. However, a noticeable increase is noted at all frequencies with an aperture on one side

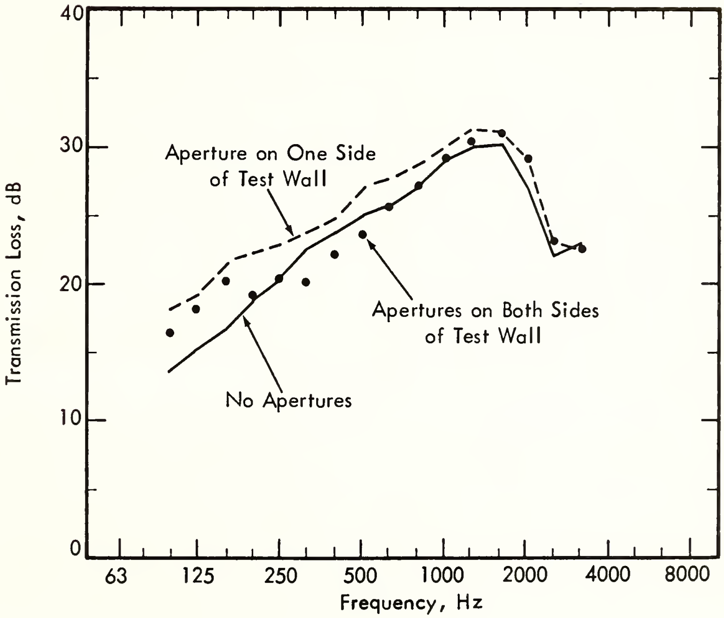

Figure 23. Data Obtained From Measurements on a Gypsum-Board Wall, Mass 10 kg/m^2, Showing the Effect of Apertures.[45]

only. These results can be partly explained by considering the coupling between room and panel modes. With a simulated aperture on one side of the wall, the acoustic modes on each side of the panel are different, resulting in poor coupling and a higher transmission loss. With apertures on both sides of the panel, the two rooms are again identical, thus reducing the transmission loss to the value without any apertures.

3.5.5 Measurement of Sound Levels

To determine the transmission loss of a structure, it is necessary to measure the space-time average sound levels in the source and receiving rooms. The criteria for the number of measurement locations required to sample adequately the sound fields in both rooms are given in the ASTM E90-75 procedure.[40] The largest allowable measurement tolerance is given at the lowest frequencies. Unfortunately, this can significantly affect the STC rating of a partition measured in different laboratories. However, unrealistically large numbers of microphone locations would be required if this tolerance were reduced. If the number of measurement locations is large, as may be the case at low frequencies in the smaller test rooms, then a large number of microphones are required in each room, together with a suitable switching network, to avoid excessive test times.

An alternative approach is to use a single moving microphone to obtain the spatial average sound level. Lubman[72] and Schroeder[73] have shown that spatial averaging over straight lines or circular paths is rather wasteful as compared to averaging the levels measured at discrete points because the variability is not decreased. However, since it may be possible to perform the spatial averaging in less time than it takes to measure the sound level at many discrete locations, the moving microphone technique may be a useful technique in some test laboratories.

3.5.6 Measurement of Receiving Room Absorption

Both the ASTM and ISO test procedures specify that the total absorption A in the receiving room is to be determined by measuring the rate of decay of sound D and using the equation

$$A = \frac{0.921\ VD}{c} \tag{10}$$

where V is the volume of the room, D is the rate of decay of sound in dB per second, and c is the speed of sound in air. If metric units are used, the absorption is given in metric sabins; if English units are used, the absorption is in sabins.

The inverse relationship between the rate of decay of sound and the room absorption was first derived experimentally by Sabine.[74] The derivation of Equation (10) is attributed to Franklin,[75] and contains the following assumptions:

- The sound energy density is uniform throughout the room before and during the sound decay.
- The sound energy is transmitted uniformly in all directions (a diffuse sound field).
- Energy is dissipated continuously with time.

The Sabine equation, perhaps more than any other in acoustics, has been the subject of long standing debate as to its applicability in non-diffuse sound fields. Eyring and Norris,[76] Millington and Sette,[77,78] and Fitzroy[79] have developed relationships for room absorption under conditions where the assumptions stated above are not satisfied. More recently, Joyce[80] has demonstrated analytically that the Sabine equation is valid in rooms where the absorption is low. Since this is generally the case in laboratory facilities, there is considerable justification for using the Sabine equation in calculating the normalization factor 10 log (S/A) necessary in the determination of transmission loss. Furthermore, errors in measuring and calculating the absorption are diluted by the logarithmic nature of the normalization factor.

3.6 The ISO 140 Standard For Laboratory Measurement of Sound Insulation

As a result of the work conducted by Kihlman and others, the International Organization for Standards has developed a modified standard for the measurement of sound insulation in the laboratory. The new standard designated as ISO 140,[81] Parts I, II, and III, was published in 1978 and replaces the ISO Recommendation R140. The most significant revisions to the standard are as follows:

- The volumes and shapes of the source and receiving rooms should not be exactly the same. A difference of at least 10 percent is recommended between the volumes of the two rooms.

- Diffusing elements should be installed if necessary to obtain a diffuse sound field.

- It is noted that theory and experiment indicate the advisability of the test panel covering the entire dividing wall or ceiling between the test rooms.

- If the test specimen is installed in an aperture between the two rooms, the aperture depths should be the same on both sides.

- Before routine testing is performed, a laboratory shall check the repeatability of the test procedure and the test setup to demonstrate the capability of producing reliable and repeatable results. Standard procedures and criteria for laboratory checks are provided in ISO 140, Part II.

- Examples are given for a suitable test procedure, for the measurement of flanking transmission, and for checking the partition loss factor.

By recognizing and addressing some of the factors that can affect the measured values of transmission loss, the revised ISO standard is an improvement over the original version. It is noted in the standard that certain aspects concerning the room sizes and test specimen mounting are still under review, indicating that subsequent revisions may be introduced at a later date.

3.7 Summary and Recommendations

A review of the available data on laboratory measurements of transmission loss shows that there is considerable variation in the values measured in different test facilities. The factors responsible for these variations are:

- The characteristics of the sound field incident to the test structure, including the effects of any aperture, and the sound field in the receiving room.
- The test structure mounting.
- The size and location of the test structure.

Insufficient understanding of these factors is the main reason for the noted differences between measured and calculated values of transmission loss. The economic implications of the variations from laboratory to laboratory can be assessed from the data shown in Figure 16. This shows that the in-place cost of a wall construction varies by about 25 percent for a change of 5 points in the STC rating.

There are strong indications that the sound field in laboratory test facilities approaches perfect diffusion except at low frequencies and in cases where the rooms are small. However, the sound field incident to the test structure does not appear to be perfectly diffuse. If this exciting sound field could be defined and measured, and specific criteria established for test facilities, then many of the problems associated with the theories of transmission loss and the interlaboratory differences in its measurement may be solved. This approach is considered preferable to those that merely attempt to increase sound field diffusion without really understanding what is, or is not, being achieved. It is therefore necessary to develop a method for measuring the sound diffusion in a room in terms of a quantity that is readily incorporated into the theoretical expressions for transmission loss.

It is recommended that proposed methods for quantifying and measuring sound field diffusion are applied in a series of experiments conducted in a transmission loss testing facility. The experiments would involve transmission loss measurements on a simple structure with simultaneous measurements of the sound field diffusion. Different degrees of diffusion could be achieved by adding absorption, by using rotating diffusers, and by introducing apertures of various types. In addition, the size of the test structure should be varied, including, if possible, one version that extends the complete width and height of the test facility rooms. The results of the experiments would be used to:

- Develop a method for measuring sound diffusion;
- Compare measured values of transmission loss with those calculated from theory incorporating a suitable representation of the exciting sound field;
- Determine the dependence of measured transmission loss on the incident sound field diffusion;
- Develop methods of increasing the sound diffusion in test facilities; and
- Develop performance criteria for test facilities.

The idea of a performance test for a transmission loss test facility is not new. An ASTM subcommittee (E33.05) is currently considering a procedure for determining the accuracy in measuring transmission loss. The procedure involves measurements on specified configurations of simple structures, the data being used to give performance information on available theories. It is possible that the data obtained from tests using the procedure will be used to develop performance criteria, at least for new laboratories.

4.0 APPLICATION OF THEORY AND MEASUREMENT PROCEDURES TO BUILDINGS

4.1 Introduction

In Chapter 2, methods have been presented for predicting the sound transmission loss of various simple and complex structures. These methods involve the use of equations relating the transmission loss to structural parameters such as mass per unit area, bending stiffness, panel separation, etc., so that the predicted values of transmission loss at each frequency are a function only of the properties of the structure. The standard laboratory test procedures[40,81] described in Chapter 3 are designed to measure the transmission loss of structures, and should provide values that can be compared with these predictions as well as with measured values for different structures on an equal basis.

If field conditions were identical to the test conditions required in the standard laboratory procedures, then laboratory measurements of transmission loss could be used to predict the sound levels in one room of a building due to a source of sound in an adjacent room. In practice, however, the conditions encountered in typical field installations differ markedly from those in the laboratory. The differences include the way in which a structure is mounted, i.e., the boundary conditions existing at the perimeter, the size of the structure, the fact that it may extend the full width and height of the rooms that it separates, and the lack of sound diffusion in the rooms. Thus, even under ideal conditions, it is often difficult to make accurate sound level predictions. Unfortunately, conditions are not often ideal in many field situations, for there are other paths by which sound can be transmitted from room to room. These so-called "flanking" paths can be summarized as follows:

- Air leaks exist in most buildings, particularly around pipe and duct penetrations, and at the perimeter edges of floors and walls.

- Airborne transmission paths exist via ventilation ducts, ceiling plenums, and through doors and common corridors.

- Part of the sound energy passes from one room to another by structure-borne paths that bypass the direct path through the intervening structure.

Finally, there is the factor related to good workmanship in construction, without which no structure can be expected to perform to its full potential.

It is not possible to account for all of these factors in predicting sound levels in buildings, and so great emphasis is placed on field measurements of the acoustic performance of structures. There are two quantities of interest in these measurements, namely:

- Field Transmission Loss (FTL) — A measure of the transmission loss or sound insulation of a structure under field conditions. The FTL is defined in exactly the same way as the transmission loss, namely, the logarithm of the ratio of incident to transmitted sound power, and for a diffuse sound field, is dependent only on the properties of the structure and the way it is mounted.

- Noise Reduction (NR) — A measure of the sound isolation between two rooms including all paths of sound propagation from one room to the other. The NR is the quantity of interest to the occupants of the building since it describes the real protection provided against noise.

It is important to note the fundamental difference between these two definitions. The field transmission loss is a property of the structure, whereas the noise reduction is a property of the structure and the building in which it is installed. The noise reduction can only be measured between rooms. The term transmission loss, defined in Chapter 2, is generally applied only to the acoustic performance of a structure as measured under controlled laboratory conditions or calculated by the methods described in Chapter 2.

The single-number rating procedure designed for application to the measurement of transmission loss (see Chapter 3.0) can also be applied to field measurements. The single-number rating for transmission loss is the Sound Transmission Class (STC). Corresponding single-number ratings for FTL and NR are Field Sound Transmission Class (FSTC) and Noise Isolation Class (NIC), respectively.

4.2 Comparison of Laboratory and Field Data

There is a considerable data base on the measured difference in the sound insulating properties of structures under laboratory and field conditions. A summary of these data is as follows:

- Berendt, et al.,[15] indicate that field measurements of the sound insulation for structures constructed with typical or normal workmanship can be as much as

8 to 10 dB lower than the transmission loss measured in the laboratory. On an average, it is stated that the degradation in performance is equivalent to a reduction of 4 or 5 points in the STC rating of the structure. With special care, the difference may be only 1 or 2 points. In some cases, field measured values exceeded those measured in the laboratory by 1 or 2 dB.

- Heebink and Grantham[82] compared laboratory (STC) and field (FSTC) data for 16 wood-framed walls and found an average difference equivalent to $3\frac{1}{2}$ STC points. When severe cases of air leakage and flanking were corrected, the average difference was reduced to $2\frac{1}{2}$ STC points. However, there were significant differences at individual frequencies that are not reflected in the STC rating.
- Jones[70] reports differences between laboratory and field measurements equivalent to a reduction in STC rating of between 0 and 8 points for wood-frame walls constructed on a wood joist floor. At some frequencies, the difference was as large as 14 dB — see Figure 24. Under certain conditions with no flanking transmission, the sound insulation was found to be up to 5 dB greater than the values measured in the laboratory.
- Lang[83] summarizes a large number of measurements conducted in Europe and shows that differences in sound insulation as large as 20 dB have been noted. As much as 10 dB difference has been noted for a given partition in different buildings.
- Zabarov[84] reports that differences in sound insulation of 1.5 to 2.5 dB have been measured in buildings with concrete walls and floors, and states that this is consistent with other reported data. However, a difference of 8 dB over most of the frequency range is reported for a floor structure of reinforced concrete with a suspended ceiling — see Figure 25.

In some of the more severe cases noted above, it is evident that some of the differences between measurements in the laboratory and in the field are due to the presence of air leaks. In the cases where attention has been given to minimizing air leaks, significant structure-borne flanking effects have been reported for some structures. The magnitude of

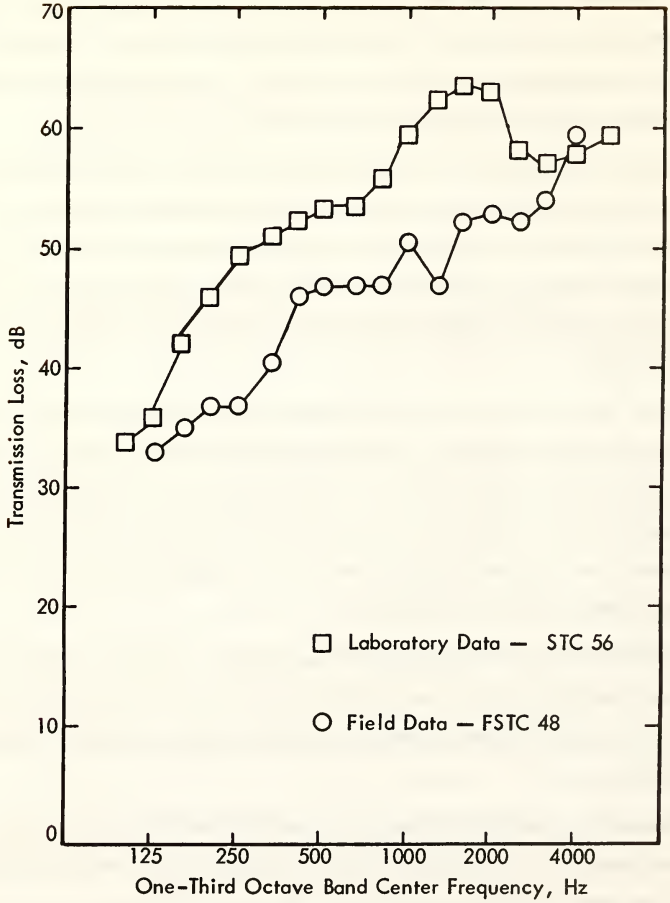

Figure 24. Laboratory and Field Measurements of Transmission Loss For a Wood-Frame Partition With Gypsumboard Mounted on Resilient Channels.[70]

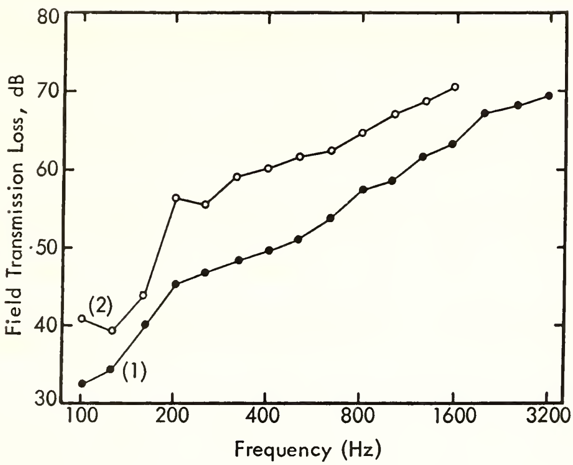

Figure 25. Floor Sound Insulation in a Building. (1) Sound Insulation Measured For a Wooden Floor With Reinforced Concrete Plates and Suspended Ceiling With Indirect Paths of Noise Transmission; (2) Measured Floor Sound Insulation With Asbestos Cement Plates Installed at a Distance From Internal Walls to Reduce Flanking Transmission.[84]

the flanking effects depends to a large extent on the physical properties of the structural elements and the way in which they are connected. Also, the difference between laboratory and field measurements generally increases as the transmission loss of the intervening partition is increased. These facts help to explain the rather wide divergence in the reported data.

If airborne and structure-borne flanking transmission is low, then the major difference between laboratory and field measurements is due to the different degrees of sound diffusion in the test rooms. In the field, rooms are generally much smaller than the standard laboratory test facilities, with the result that the modal density at any given frequency is correspondingly lower. Thus the effects caused by lack of sound diffusion that were discussed in Chapter 3 are magnified in the typical conditions where field measurements are required. Moreover, the presence of uneven amounts of absorption on the floor or ceiling can change the characteristics of the sound field considerably, particularly at the sensitive grazing angles of incidence. Recalling the discussion in Chapter 3 on the effect of sound diffusion on the measured transmission loss, it is not surprising that laboratory and field results do not agree. It should be emphasized, however, that the effect of poor sound diffusion generally results in an <u>increase</u> in the noise reduction between rooms, whereas flanking transmission will, of course, decrease the noise reduction. Jones[70] has found that these two factors may counteract one another resulting in a field performance equal to that predicted from laboratory results.

The presence of air leaks and other airborne flanking paths can significantly reduce the acoustic performance of structures in buildings. However, the methods for eliminating these paths are well known and are documented in guidelines for building noise control.[15] Therefore little more need be said on this subject, except that the available methods need to be implemented in the design process, and workmanship needs to be checked during construction.

Summarizing the data reported in the literature, and extracting that which appears to be dominated by airborne flanking paths, it appears that the measured field transmission loss of a structure can be from 10 dB less to 5 dB greater than the transmission loss measured in the laboratory. A typical range would be -5 to +3 dB.

4.3 Prediction of Noise Reduction in Buildings

In the design of a new building, the architect must select building elements, such as walls, floors, and ceilings, that meet the requirements of the applicable building codes. Where these codes include a consideration for acoustical privacy between adjacent rooms or dwellings, it is common for the requirements to be specified in terms of the STC rating of the elements, as determined from laboratory measurements. According to the data presented in the previous section, this approach to noise control may result in the noise reduction between adjacent rooms being in the range 5 dB less than, or in some cases up to 5 dB greater than, the design value. These facts are known by many architects who tend to compensate for the apparent discrepancy by overdesigning the elements. It is in fact common to assume a discrepancy of between 3 and 5 dB between laboratory and field performance of building elements. The term "apparent discrepancy" is used here because the building elements themselves are not always at fault. The real culprits may be poor sealing at the perimeter, and airborne or structure-borne flanking. If this is so, then overdesigning the building element may have little or no effect on the noise reduction, although the building costs will most certainly be higher. Using the data shown in Figure 16 for typical structures, overdesign by 5 STC points can increase the material cost by about 25 percent. Thus the use of laboratory data can lead to inadequate acoustical privacy in the finished building, as well as increased building costs.

As an alternative to using laboratory data, acoustical engineers will sometimes perform predictions of noise reduction with data obtained from field measurements, where these are available. Provided that the field data were taken for constructions without air leaks or airborne flanking paths, and that the finished building will incorporate the same precautions, this approach can lead to better predictions of noise reduction. However, there is still the danger that structure-borne flanking, which can vary significantly for different building types, may be present and render the predicted values too high. If the measured field data were obtained in a building similar to the one under design, then it may be reasonable to assume similarities in flanking transmission. Under this condition, the factors that reduce the accuracy of the predicted noise reduction are:

- Differences in the sound field in the rooms where the data was collected and in the rooms under design.

- Differences in construction from the structure for which field data are available.
- Poor workmanship in construction.

A problem does exist in designing exterior building structures simply because there is limited data for some of the building elements. This is particularly true for roof/ceiling systems, which, because of their large area, can be extremely significant paths of sound transmission. Although these are exceptions, most guidelines on building noise control completely ignore this important element. The transmission loss of a roof/ceiling system is not easy to measure in the laboratory, so that there is heavy dependence on field measurements, with all the inaccuracies that are inherent in these data.

The other major element that determines the noise reduction of a building structure is the window. In this case there is an abundance of data for many different window designs tested in the laboratory, some of which must be regarded as dubious at best. The problem lies in the application of the laboratory test procedure to the usually small window sizes available. Although it is certainly true that the size of the test specimen is representative of field application, the placement in the test facility wall may be critical — see Chapter 3. Moreover, the exterior sound field cannot under any circumstances be considered diffuse, so that the field performance may be quite different to that predicted by the laboratory test results. In this context, prediction methods suffer from a lack of knowledge of the transmission properties of structures as a function of the angle of sound incidence.

Predicting the noise reduction of existing building structures is generally difficult because the structural composition may not be obvious from a visual inspection, and relative movement of the structures or warping of the wood may introduce air leaks. The prediction is particularly difficult for exterior structures with windows and doors, where perimeter caulking has dried and shrunk, and where the weatherstripping has deteriorated. Much of the data on the accuracy of prediction methods for exterior structures is contained in the files of acoustic consultants and hence is inaccessible. However, data obtained from Wyle files[85] indicate that the mean difference between predicted and measured values is zero with a standard deviation of about 2.5 dB. Thus measured values can be predicted to within ±4 dB with a 90 percent confidence. Such predictions are normally required to identify the steps that need to be taken to soundproof existing buildings from exterior noise. Ideally, the prediction process should be accompanied by measurements, the latter to

determine the actual noise reduction, the former to identify the major paths of transmission. By inspecting the measured noise reduction in different frequency bands it is then possible to detect the presence of air leaks, and take them into account in the prediction process. Usually, air leaks occur at the perimeters of windows and doors, and, since the first step in soundproofing is to seal the leaks, it may not be too important that the predictions are in error, provided that measurements are performed to identify the need for soundproofing in the first place.

4.4 Field Measurement Procedures

Although laboratory measurements are necessary to provide comparative data for different structures under controlled conditions, it is clear from the last two sections of this chapter that the data obtained do not necessarily represent the performance achieved under field conditions. Field measurement procedures provide data to evaluate the field performance of structures when they are installed for their designated use. Specifically, they are used as follows:

- To verify that the design noise reduction is achieved in the final construction.
- To verify that each individual element is performing to its potential, particularly if it is found that the design noise reduction is not achieved.
- To provide the basis for the design of modifications necessary to increase the noise reduction in existing buildings.
- To develop a comprehensive data base of field measurements to identify trends in acoustic performance and common problems that need to be addressed in design.

There are basically two types of field procedure required, one to measure noise reduction between rooms, the other to measure the field transmission loss of individual elements. Such procedures must be available for application to interior and exterior structures. The different types of field procedures that are designed to measure noise reduction and field transmission loss as a function of frequency (in octave or one-third octave bands) are discussed in the following sections. Procedures for measuring single-number values of noise reduction are discussed in Section 4.5.

4.4.1 Measurement of the Field Transmission Loss of Interior Structures

The field transmission loss (FTL) of a structure is a measure of its transmission loss under field conditions and is generally only measured when measurements of noise reduction between rooms show lower results than originally predicted. The FTL cannot be used to calculate the noise reduction between two rooms because factors such as flanking transmission that degrade the field performance of structures are deliberately excluded in its definition. The usefulness of the quantity FTL is therefore limited to comparing the field performance to the maximum potential performance as measured in the laboratory. In this respect, it is a useful diagnostic tool.

In terms of measurable parameters, the field transmission loss of a partition is defined as follows:

$$FTL = \overline{L_1} - \overline{L_2'} + 10 \log (S/A) \tag{11}$$

where $\overline{L_1}$ is the average (over space and time) sound pressure level in the source room; $\overline{L_2'}$ is the average (over space and time) sound pressure level in the receiving room as a result of sound radiation from the partition only; S is the area of the partition; and A is the absorption in the receiving room. The factor 10 log (S/A) is included to normalize the difference in sound levels to a standard condition, theoretically making the value of FTL independent of the receiving room characteristics.

To measure the field transmission loss it is therefore necessary to eliminate airborne and structure-borne flanking transmission. Even with this precaution, the measured values will not necessarily be the same as those measured in the laboratory. The lower sound diffusion in small rooms will tend to provide higher values of FTL than in the laboratory, whereas the size of the structure with respect to the source and receiving rooms will tend to give lower values, as discussed in Chapter 3.

The ASTM E336-77[44] procedure for field measurement specifies certain conditions that must be met for the results to be as independent as possible of the sound fields in the two rooms and the building in which the structure is installed. For example, the procedure is valid only at frequencies equal to or greater than a lower limiting frequency that is a function of the room volume. In fact, for any given lower limiting frequency, the minimum

room volume is about one-half that recommended for laboratory facilities in the ASTM E90-75[40] procedure. Judging by the results presented by Higginson,[46] whose test rooms would be suitable at frequencies equal to and greater than 250 Hz, this criterion may lead to poor repeatability at the lower and even medium frequencies. In small rooms it is difficult to increase the sound diffusion because the size of the diffusing elements necessary to modify the low-frequency modes would be comparable to the room dimensions, leaving very little space for suitable microphone locations.[86] Thus poor diffusion must be accepted in the measurement of field transmission loss.

If significant flanking transmission exists between the source and receiving rooms, then steps must be taken for its reduction before the FTL can be measured. The E336-77 procedure provides guidance in determining whether flanking transmission exists by specifying a number of qualitative and quantitative tests. A mandatory test involves adding a temporary shield to the partition and repeating the FTL measurements. This test is discussed more fully in Chapter 5 — it is sufficient here to say that it is a most complicated and time-consuming test that is totally unsuited to routine testing in the field.

The ISO 140/IV[81] procedure for the measurement of sound insulation of building elements is somewhat confusing as it does not differentiate between sound insulation and the sound isolation (or noise reduction). In addition to the normalized noise reduction, NNR, defined as follows:

$$NNR = \overline{L_1} - \overline{L_2} + 10 \log (T/0.5) \tag{12}$$

where T is the receiving room reverberation time in seconds, it introduces a term called the "apparent transmission loss", R', which is the transmission loss of a partition as if all the sound energy reaching the receiving room passed through the partition, and is defined as follows:

$$R' = \overline{L_1} - \overline{L_2} + 10 \log (S/A) \tag{13}$$

assuming diffuse sound fields in the two rooms.

The quantity R' is the same as the quantity FTL only in the absence of flanking transmission. Thus the ISO procedure does not in fact measure the field transmission loss or sound insulation of a partition, but only two versions of the noise reduction with different normalization factors.

There are two methods given in the ISO procedure for measuring flanking transmission. One of these involves the use of additional shields to the test structure, similar to the ASTM E336 procedure. The other requires a measurement of the average velocity levels of the test structure and other surfaces in the receiving room. This data is then used to calculate the sound power radiated by each surface, and hence the contribution from structure-borne flanking transmission. The method of calculation is satisfactory for massive structures of concrete or masonry, where the radiation factor is known to be close to unity over most of the frequency range of interest. For the test structure, which is excited directly by the sound field in the source room, the radiation factor is also close to unity at most frequencies. However, for frame walls with high critical frequencies, the value of the radiation factor is unknown at low and medium frequencies — see Chapter 5. In this case, the flanking contribution cannot be accurately calculated.

4.4.2 Measurement of Room Absorption

To determine the field transmission loss of a structure it is necessary to measure the amount of absorption in the receiving room so that the final value of FTL is independent of the receiving room characteristics. The ISO and ASTM standards for field measurement of transmission loss provide two alternative methods for measurement of absorption in the receiving room. The first method follows the laboratory approach of measuring the time decay or reverberation time of the enclosed sound field and calculating total absorption by application of the Sabine relationship — see Chapter 3. The alternative method is to measure the spatial average sound pressure level, $\overline{L_2}$, in the room produced by a standard source of known sound power output, L_W, and insert the value in the following equation:

$$A = \text{antilog}\,(L_W - \overline{L_2} + 6.2)/10\ \text{, metric sabins} \qquad (14)$$

Cook and Proctor[87] describe an elegant way of using a standing wave tube apparatus to provide an absolute sound power reference source which can be used for such absorption measurements. Although under idealized diffuse field conditions the reference source measurement provides absorption values identical to those derived from decay measurements, caution should be exercised for applications to rooms with high absorption. As discussed in Reference 88, the use of the reference source method in rooms with high absorption results in a higher relative contribution of the initial reflections which are not randomly distributed thus restricting the range of validity of the measurements.

Both methods for measuring absorption rely on equations developed under the assumption that the sound field is diffuse — a questionable assumption in small rooms. Factors that limit the degree of diffusion are as follows:

- The volume of the room is so small that isolated acoustic standing waves are in evidence at lower frequencies where FTL measurements are required. Diffuse field conditions require the existence of many overlapping acoustic resonances down to the lowest frequencies tested.

- Because of symmetry in the shape of the room, certain room modes or groups of modes contain a disproportionate share of the energy. Extreme examples would be cubical or spherical shaped rooms.

- As the absorption in the room is increased, the direct field from the sound source becomes predominant over an increasingly large area.

- The concentration of sound-absorbing materials in the room affects the distribution of sound energy. This can occur when the absorbent material is placed on one or two surfaces in the form of a carpet or ceiling tiles.

Deviations from diffuse field conditions affect the measurement of room absorption in several ways. In a non-diffuse field, the time decay of sound pressure level can differ significantly from a linear relationship. A decay response with a continuously changing slope presents a problem in defining a unique absorption value. In a non-diffuse field the sound level as well as reverberation time will show considerable variation with position within the room. Obtaining a spatial average value, even if such a value has meaning, requires a large number of measurements. Most importantly, under non-diffuse conditions, the established relationships between room absorption and either reverberation time or sound pressure generated by a standard source is no longer valid.

An additional factor affecting the sound diffusion in the receiving room is the type and location of the sound source.[46] In the source room, the source of sound is a loudspeaker placed close to one of the corners to excite as many room modes as possible. In the receiving room, the "source" of sound is the test structure that couples to the room modes in a different way than a small source. Therefore, even if the sound field in the source room were diffuse, this does not necessarily mean that the field in the receiving room (of the same size) is

diffuse. In general, the latter will be less diffuse. Since the measured absorption in a room is a function of the sound field diffusivity, the correct value of absorption for the normalization factor cannot be deduced from reverberation time measurements obtained using a small source placed in the room corner. The actual error introduced by assuming a diffuse sound field in the receiving room is not known, because the effect of sound diffusion on measured absorption is not well understood.

4.4.3 Measurement of Noise Reduction Between Rooms

The noise reduction (NR) between two rooms is a measure of the protection afforded an occupant in one of the rooms from noise in the other room. It is defined as the difference in spatial average sound pressure levels in the two rooms, namely,

$$NR = \overline{L_1} - \overline{L_2} \tag{15}$$

In contrast to the field transmission loss, which is a measure of the field performance of a specific structure, the noise reduction between rooms includes all paths of transmission, direct and flanking, and so cannot be directly related either to FTL or the transmission loss measured in the laboratory. Furthermore, the term "noise reduction" can be used to describe the protection provided from sources of noise in non-adjacent rooms.

The measurement of noise reduction is performed in exactly the same way as the measurement of field transmission loss, with the exception that no attempts are made to eliminate flanking transmission or to achieve diffuse sound fields in the measurement rooms. Thus the measured values represent the protection that the eventual occupant will experience. Of course, it is possible to increase the noise reduction merely by adding absorption to the receiving room. If the measurements are performed with the receiving room furnished by the occupant, then the measured noise reduction requires no correction. However, it is, or should be, common practice to perform the measurements at the completion of construction with all rooms empty. Under these conditions, the measured noise reduction will in general be less than that experienced by the occupant for the following two reasons:

- The addition of furnishings in the receiving room will increase the receiving room absorption and hence lower the sound level.

- The addition of furnishings, particularly carpets and ceiling tiles in the source and receiving rooms, will decrease the sound diffusion and may increase the measured transmission loss of the partition separating the two rooms.

The effect of receiving room absorption can be accounted for by normalizing the measured noise reduction to a reverberation time of 0.5 second. The normalized noise reduction, NNR, is thus given by Equation (12). A standard reverberation time of 0.5 second is chosen because it closely represents the typical value for most furnished rooms. If it is inconvenient to measure reverberation time (this requires additional equipment), it is claimed that a good approximation can be obtained by using the following expression:[89]

$$NNR = \overline{L_1} - \overline{L_2} + 10 \log (S_f/A) \qquad (16)$$

where S_f is the floor area. In this case, the receiving room absorption, A, can be measured using a source of constant and known sound power. The problems of determining absorption in small rooms has been discussed in Section 4.4.2.

The effect of absorption on the transmission loss of a structure cannot be accounted for with the current understanding of sound field diffusion. According to data collected by Jones,[70] the normalized noise reduction between two empty rooms may be lower by as much as 3 to 5 dB than the actual noise reduction achieved when the rooms are furnished. Additional data are required to determine whether this range is typical.

4.4.4 Measurement Procedures For Building Facades

Historically, the efforts to develop test procedures for measuring the acoustic performance of structures have concentrated on interior building elements, leaving methods suitable for building facades to the discretion of the acoustical consultant. General guidelines for such measurements are given in Appendix A2 of the ASTM E336-77[86] procedure, but these allow significant and important variations within the stated conditions. Accordingly, data for building facades have been presented in a variety of forms. The recent interest in providing protection for buildings against the external noise produced by highway traffic and aircraft, and for soundproofing existing buildings, has led to the requirement for a much more closely controlled test procedure. As a result, the International Organization for Standardization has established a standard test procedure — ISO 140/V[81] — and an

ASTM subcommittee is currently working on the draft version of a similar procedure. Both procedures require an exterior source of sound and measurements of the sound level inside and outside the building.

Unlike the measurement procedures for interior building areas, the noise reduction and field transmission loss of building facades depends on the noise source characteristics. The exterior sound field often consists of progressive waves radiated from the source with few reflections from nearby obstacles. For a point source, such as a single piece of machinery, the sound will be incident on the building facade at a single angle of incidence. For a line source, such as a highway, or for aircraft overflights, sound will be incident at many angles. To account for this fact, both the ISO and draft ASTM procedures allow for measurements to be performed using highway noise or loudspeakers as the sound source. The field transmission loss, FTL, of the facade is given by the following expressions:*

$$\begin{aligned} &\text{For Highway Noise:} \quad FTL = L_{eq,o} - \overline{L_{eq,i}} + 10 \log (S/A) \\ &\text{For Loudspeakers:} \quad FTL = L_o - \overline{L_i} + 10 \log (S \cos \theta/A) \end{aligned} \tag{17}$$

where L_o is the exterior sound pressure level; $\overline{L_i}$ is the spatial average of the interior sound pressure level; the subscript "eq" referring to the equivalent sound pressure level; and θ is the angle of incidence of the incident sound measured from the normal to the facade. The ISO procedure also allows for the measurement of normalized level difference (noise reduction), D_n, defined as follows:

$$D_n = L_{eq,o} - \overline{L_{eq,i}} + 10 \log (T/T_o) \tag{18}$$

where T_o is 0.5 second for dwellings.

For traffic noise, both procedures recommend that the exterior sound level $L_{eq,o}$ be measured 2 meters away from the exterior facade, although an alternative location very close to the facade surface is allowed if the surface is smooth. In the latter case, 3 dB is subtracted from the value of FTL calculated from the above expressions.

* The draft ASTM procedure uses the term "transmission loss" rather than field transmission loss. Strictly speaking, the above expressions represent the noise reduction normalized by the factor 10 log (S/A), since flanking transmission may occur. In practice, windows are the weakest element of the facade, flanking transmission should be negligible, and the difference in terminology is not important.

Using the loudspeaker as a source, the exterior level L_o in the ISO procedure is the level that would exist at the facade surface if there were no reflections, i.e., it is the sound level that would be produced at that distance in the absence of the surface. The draft ASTM procedure also allows for measurements to be taken 2 meters from the facade. Unfortunately, there is very little available data on the relationships between the different microphone locations, or between the use of traffic noise and a loudspeaker as the sound source.

The draft ASTM procedure states that for measuring FTL using highway noise as the source, the roadway should be straight and parallel to the building facade. Other highway configurations can be used, but the data should not be used to develop data for general applications. This procedure is apparently aimed primarily at developing a data base for different constructions. There remains the question — how does one check that a facade is performing to its field potential if the highway configuration is complex? The loudspeaker method can be used to check the building construction only if there is carefully controlled data available for comparison.

Lewis[90] has performed measurements of field transmission loss using highway noise and incorporating an average value of the $\cos\theta$ term in Equation (17), the value of θ being obtained analytically for each highway configuration. This additional factor enables the length of the roadway and the elevation of the building to be taken into account, whereas the draft ASTM procedure specifies limitations on both these quantities. Using this method, Lewis shows that the field transmission loss for a facade on the ninth floor is from 3 to 5 dB less than that for a similar facade on the first floor. However, because of the difference in the angle of sound incidence, the noise reduction, and hence the protection provided to the occupant, is about the same at the two elevations.

The ISO procedure allows much greater flexibility than the proposed ASTM method in highway location and so the measured data can be expected to show larger variations from building to building. The actual effect of highway complexity and location with respect to the building facade is not well documented, so that the magnitude of the variations is unknown. In this context, neither procedure addresses the method of measurement for corner rooms, or for roofs, which are of major concern in buildings near airports.

The measurement of the interior sound levels and absorption are subject to the same problems discussed in the previous sections. There are insufficient data available to comment on the repeatability of the two procedures, but Lewis presents limited data to show that it compares favorably with the repeatability of field noise reduction measurements between interior spaces.

4.4.5 The Repeatability of Field Measurements

The repeatability of field sound insulation measurements has been studied at considerable length by Higginson[46] and Fothergill,[91] by means of an experimental study conducted in a laboratory house. The spread of measured results taken by 12 organizations on a 23 cm solid brick party wall have been described in Chapter 3. Following this initial phase of the study, Higginson used several variations of loudspeaker size, cabinet design, location and orientation, and found noticeable variations in the sound field for each configuration. In most cases, however, the sound level uniformity at low frequencies was increased significantly by adding absorption to the room, although the reverse was true at high frequencies. The addition of absorption to the receiving room alone increased the normalized noise reduction (the difference in sound levels in the two rooms normalized to a reverberation time of 0.5 sec) by 1.5 dB on average over the frequency range 100 Hz to 3150 Hz, although increases of up to 4 dB were noted at medium and high frequencies. Similar results have been reported by Jones.[70] Higginson acknowledges that the normalization procedure is not justified with such non-diffuse conditions, and so it is uncertain that there is an actual increase in transmission loss or whether it is an artifact of the absorption measurement used for normalizing the level difference. If the latter is the case, then the implication is that the measured absorption is lower than the actual absorption in the receiving room. Since there are strong indications (see Chapter 2) that sound diffusion can affect the measured transmission loss, the measured increase in normalized noise reduction may be due to a combination of both effects.

It was also found that temperature differences between the source and receiving rooms tended to increase the measured noise reduction. This increase was essentially nullified by adding absorption to the receiving room. These results illustrate the effect of modal matching between the two rooms. Adding absorption <u>or</u> changing the temperature

in one of the rooms effectively mismatches the modes and increases the noise reduction. With the added absorption, changing the temperature in one room has little effect because the modes are already mismatched.

Fothergill[91] reports the results of a series of field tests conducted by 7 different measurement teams showing that the standard deviation of the noise reduction is in the range 1 to 2 dB at frequencies below 500 Hz, and about 1 dB at higher frequencies. A small but significant improvement in repeatability was achieved by devising rules for source and microphone locations.

Utley[92] has shown that as many as 20 microphone locations may be required to obtain the average one-third octave band sound pressure level with a 95 percent confidence in small rooms at low frequencies. The number of locations can be reduced by a factor of 2 by using octave band measurements. The ASTM E336-77 field measurement procedure specifies a required number of measurement locations based on the spread of the data in order to achieve a precision of ±1 dB with a 90 percent confidence. For example, if the range between the highest and lowest sound level measured is 5 dB, then 10 measurement locations are required.

In an attempt to reduce the time necessary to obtain the average sound level while maintaining the same confidence in the results, continuously moving microphones have been proposed. Simply rotating a microphone along a circular path may not adequately sample the sound field in small rooms. A more complex path involving both horizontal and vertical motions has been proposed by Rohrberg,[93] and also by Higginson,[46] who demonstrated that the mean sound level deviation (over 16 one-third octave bands) between this procedure and a large number of stationary microphones is less than 0.5 dB. By using a moving microphone, the time required for testing can be reduced by a factor of 4. The disadvantages of the method for use in the field are the requirements for a device to provide the complex motion, and an instrumentation system capable of time-averaging the sound level.

In summary, the repeatability of field measurements conducted in typical sized rooms is generally poor unless considerable care and time are taken to sample adequately the sound field in each room. The problem is particularly acute at low and medium frequencies where sound diffusion is low.

4.5 Descriptors For Sound Isolation

4.5.1 Descriptors Based on Weighted Level Differences

Descriptors based on grading curves (see Chapter 3) may be suitable for describing the potential transmission loss of a structure from laboratory measurements, but are unsuited to routine field measurements because of the large amount of one-third octave band data that must be obtained. If a single number descriptor is required, it makes sense that the sound level measurements should be taken in terms of a single number, at least for enforcement of building code provisions in the field. Several workers have noted that a good agreement exists between descriptors based on grading curves and the difference in weighted sound levels between rooms separated by a partition.[42]

Siekman, et al.,[94] have suggested a simplified test for the field performance of structures, using a pink noise source and measurements of the A-weighted sound pressure level in the source and receiving rooms. It was found that the difference in the sound levels, normalized by the factor 10 log (S/A), agreed very well with the STC rating of the partitions between the two rooms for many different building constructions. The standard deviation of the difference between the results obtained by the simple test and the standard E-336 procedure was reported by Siekman to be about 1 dB. As noted by Schultz,[95] this agreement was quite fortuitous because the measurements were in fact of noise reduction or apparent transmission loss R' as defined in ISO 140, including flanking transmission, and the STC rating represents only the transmission loss of the separating partition. In the general case, where flanking may be present, the difference in A-weighted sound levels should be compared to the NIC rating. Quindry and Flynn[96] show that, for unfurnished rooms, the standard deviation of the A-level difference minus the NIC rating is about 0.8 dB. Flynn[97] recommends measurements of the C-weighted level in the source room and A-weighted level in the receiving room.

Brittain[98] shows that the agreement is not so good for some structures — differences of up to 5 rating points were noted by using the simplified procedure in a laboratory test facility. He ascribes the reason for poor agreement to the inability of the simplified test to account for the low transmission for some partitions at low frequencies.

Although there appears to be good agreement between weighted level differences and the NIC rating, this does not justify their use in building codes because, as noted

previously, there is considerable uncertainty as to the validity of the NIC grading procedure. In fact, it has been shown by Schultz,[99] using a data base of 35 case histories, that both the NIC rating and the weighted level difference by themselves correlate poorly with the subjective response of building occupants. But when either of these quantities is combined with the source level, source room absorption, the degree of privacy required, and the background noise level in the receiving room, the correlation improves considerably. Moreover, the correlation is not a strong function of the source spectrum used in calculations of the weighted level difference. Since it is inconvenient to include all five factors, it has been suggested[99] that an appropriate descriptor for use in building codes is the Privacy Index I_p, which is the sum of the A-weighted level difference, ΔL_A, between two rooms and the A-weighted background noise level, N_A, in the receiving room.

$$I_p = \Delta L_A + N_A \tag{19}$$

Using data developed by Young,[100] Schultz[99] suggests indices of 85 for confidential privacy or high-rent dwellings, and 73 for less critical situations. In applying the Privacy Index concept to building codes, it would, of course, be necessary to stipulate a maximum allowable value for the background noise level, N_A. One of the advantages of this concept is that the index I_p is independent of the absorption in the receiving room — absorption has an equal and opposite effect on the quantities ΔL_A and N_A, respectively. The disadvantage is that the correlation with subjective response is not much better than for ΔL_A or NIC alone.

A rating scheme for building facades has been developed by Mange, et al.,[101] to facilitate the calculation of interior A-weighted sound levels produced by transportation noise sources. It is based on the rationale that the interior noise spectrum should have the characteristics of the 40 dB equal loudness contour, which is an inverse A-weighted response curve. On this basis, the transmission loss characteristics of an exterior structure can be evaluated if the exterior noise spectrum is identified. The result is an Exterior Wall Noise Rating (EWNR) for the structure. Different correction factors must be applied to the EWNR to account for the variation in spectra from different transportation noise sources. As a method for ranking the performance of exterior facades in terms of subjective response, this method suffers from the same criticisms given to other grading procedures — see Chapter 3. However, it is a useful method for calculating the reduction in A-weighted sound levels between the outside and inside of a building.

4.5.2 Measurement of Weighted Level Difference

Based on the relative simplicity of performing measurements of weighted level difference as compared to the NIC, the ASTM has approved a Tentative Recommended Practice E 597-77T.[102] The procedure involves measurement of the A-weighted sound levels in the source and receiving rooms, with a specified random noise spectrum established in the source room. The source spectrum is specified to be within a given range, this tolerance following from the discussion in the previous section.[103] Provisions are also made for measuring the absorption (A-weighted) in the receiving room using a source of constant power and specified spectrum, so that the level difference can be normalized if necessary. Note that the normalization is not required in the calculation if I_p.

A rapid procedure for measuring the noise reduction between rooms has also been suggested by de Tricaud[104] using a pistol shot as the source of sound. The quantities measured in the source and receiving rooms are the integrals over the pistol shot duration of the squared sound pressures — proportional to the sound energy. In a series of measurements on different structures, de Tricaud shows good agreement between the octave-band noise reduction measured by this method and by the more normal method using a steady-state source. The mean difference in A-weighted sound isolation measured by the two methods was found to be 0.5 dB, with a standard deviation of 1.1 dB. The method using pistol shots requires the use of an analogue integrator specially built by de Tricaud for the project, but the integration could be performed by modified sound level meters that are designed to measure impact noise energy.

4.6 Summary and Recommendations

The data presented in this chapter show that the transmission loss of a structure measured in the laboratory can be anywhere in the range 0 to 10 dB greater than the noise reduction, normalized by the factor 10 log (S/A), between rooms separated by the same structure. The reasons for the difference are the presence of flanking transmission and the dimensions and mounting of the structure in the field relative to the laboratory installation. In some cases, it is possible to note an apparent increase of up to 5 dB in the acoustic performance of a structure due to an extreme lack of sound diffusion in the rooms, particularly when the rooms are small. As a result of these differences, prediction methods for new buildings using laboratory measured data can be high by as much as 10 dB or low by as

much as 5 dB, depending on the field conditions. A typical range would be +5 to -3 dB, similar to the accuracy of predicting the noise reduction for existing structures using available field measured data.

To increase the accuracy of prediction methods, it is necessary to obtain a better understanding of the following factors:

- Flanking transmission between rooms.
- The effect of sound field diffusion on the transmission loss of structures.
- The effect of structure size on transmission loss, i.e., wall-to-wall, floor-to-ceiling structures versus baffled structures as tested in the laboratory.
- The effect of sound absorption on the space-averaged sound levels in a room.

The first of these factors is addressed in Chapter 5 of this report; the second and third factors have already been addressed in Chapter 3. To provide the information applicable to field predictions, the study recommended in Chapter 3 needs to be extended to include small rooms. In particular, it would be interesting to determine if any significant increase in transmission loss can be achieved by designing for low sound field diffusion. Thus this study should consider the effect of absorption and its placement on the transmission loss of structures.

Sound Field Sampling

The measurement of field transmission loss and noise reduction is performed in essentially the same way as in the laboratory. However, the typical small room sizes encountered in the field require additional microphone locations to sample the sound field adequately at low and medium frequencies. The testing time can be reduced significantly without reducing accuracy by using a rotating microphone together with a suitable time-averaging network, but such a system is cumbersome for use in the field. An alternative method for sampling the sound field is to place a single microphone in the room corner, where the amplitude of all modes is a maximum. The corner location would not only reduce the time required for measurements, but would also eliminate any uncertainty as to where the microphones are placed. Further work is needed to establish the validity of this deterministic approach to sound field measurement, and to identify which of the room corners is most suitable.

The purpose of measuring the noise reduction between rooms is to determine the speech privacy the eventual occupants will enjoy, and the protection they will be afforded from noise in adjacent dwellings. Therefore measurements of the sound level in the receiving room are only required at locations where the listener's head is likely to be located. It is not necessary or desirable to perform a spatial average of the sound level throughout the entire volume of the room. It is more realistic to measure the average sound level at the noisiest locations in the room normally occupied by the listener. These locations will often be closest to the source of noise and near the walls of the receiving room – locations normally excluded in the spatial average required by the standard ASTM E336-77 test procedure.

A recommended procedure for selecting microphone locations in measuring sound levels in rooms is given in the draft standard method for measuring and rating room noise prepared by members of the ANSI Working Group S3-S7-S1. It is necessary to gain experience with this procedure and gather data to establish its validity.

Normalization

Since noise reduction measurements are normally performed before the rooms are furnished, it is necessary to take account of the increase in absorption, and hence noise reduction, that the furnishings will provide. This is normally achieved by correcting the measured noise reduction to a reverberation time of 0.5 second which is fairly typical in furnished dwellings. Alternative corrections involving room absorption have been developed to eliminate the need for measuring reverberation time. The problem, however, is that adding absorption increases the measured normalized noise reduction. Whether this is a result of decreased sound diffusion increasing the transmission loss of the dividing partition, or errors in determining the room absorption, or both these factors, is not known. What it means is that the noise reduction measured and normalized in unfurnished rooms will reflect a lower value than that achieved with the rooms furnished. The discrepancy may be as much as 5 dB at some frequencies, or approximately 3 points in the Noise Isolation Class (NIC). A more realistic value of the noise reduction between rooms that will be subsequently furnished can be obtained by performing the measurements with absorption in both source and receiving rooms. The amount of absorption ideally should be representative of typical furnishings, but it may turn out that this is not a strict requirement. The noise reduction

measured in this way can then be normalized to a reverberation time of 0.5 second, so that the value achieved for any given degree of furnishing can be calculated where necessary. Before such a procedure is adopted, the relationship between noise reduction and absorption needs to be understood. The introduction of absorption in this way will also reduce measurement uncertainties caused by mode matching between rooms of equal size.

Absorption Measurement

The actual method of normalizing values of field transmission loss or noise reduction by measuring the room absorption is subject to two kinds of errors. First, the single source used for reverberation or constant sound power measurements excites the room modes in a different way than the partition that transmits the sound energy from the adjoining room. It is not known if this difference is significant. A possible alternative method for determining the room absorption is to calculate the sound power radiated by the partition with a sound source in the source room. This can be achieved by measuring the average velocity of the partition and assuming a radiation factor of unity — not an unreasonable assumption for the radiation of forced waves. The absorption is then calculated using Equation (14). If this procedure was found to be suitable, the velocity measurements could be performed at the same time as the sound levels in the two rooms are measured. Incidentally, in the absence of flanking transmission, the field transmission loss could then be determined without the need for sound level measurements in the receiving room, as can be seen by combining Equations (10) and (14). Experiments are required to test the need for, and feasibility of, this procedure, to ensure that a completely different set of errors are not introduced.

The second error in the normalization process, and one that applies equally to the alternative procedure described above, arises through the use of statistical sound field theory to calculate the room absorption. In the laboratory the experimental conditions can be controlled to achieve a high degree of diffuseness in the receiving room, thus permitting a reasonably accurate measurement of sound absorption. In field application such ideal experimental conditions are rarely approached. In the field, therefore, the uncertainty introduced in absorption measurements contributes to the difficulty in obtaining accurate field transmission loss values. A recommended area for future research is therefore a more concentrated study of the acoustical characteristics and absorption measurements in actual habitable rooms.

An approach to evaluating absorption in a non-diffuse room follows from the conventional practice of relating the rate of decay of sound to total absorption. In a non-diffuse field, a decay rate will be more sensitive to source and receiver position thqn for a more diffuse field. Sound decay resulting from termination of a sound source may or may not be linear with time. A variety of curve-fitting or other graphical techniques are available to provide a measure of slope or degree of curvature of the decay time history. Sampling a decay parameter at a variety of locations in the room will provide a set of decay data which can be analyzed either statistically or as a function of position within the room. The relationship between these data and absorption within the róom can be explored either theoretically, making use of the various conceptual room acoustic models, or empirically, by means of experimental programs or computer simulations.

An approach which may have some promise in measuring absorption within a non-diffuse field involves the concept of introducing infrasonic amplitude modulation to a sound source within a room. Cook[105] describes a technique for use in diffuse sound fields by which a measurement of the degree to which the phase of the modulated sound field lags the phase of the sound source can be simply related to total absorption. The difficulty in applying this technique in a non-diffuse sound field lies in the resulting spatial variation of phase throughout the room interior. Further experimentation, however, may yield a method by which the phase variation within the room can be either compensated for or integrated into a relationship for the total interior absorption. This approach may be too cumbersome for field application, but may be useful in laboratory studies of non-diffuse sound fields.

Without fully understanding the characteristics of non-diffuse sound fields, and their relation to the amount and location of absorption, suitable methods of absorption measurement in the field cannot be developed. Therefore a first priority must be to examine the type of sound fields produced in real buildings and the influence of room parameters on sound diffusion.

Flanking Transmission

The current ASTM E336-77 procedure for measuring the field transmission loss of a structure in the presence of flanking transmission is cumbersome in the extreme and is totally unsuited to routine field measurements. Structure-borne flanking can be identified

in many cases by measuring the velocity of the room surfaces, provided that some guidance is given to account for the radiation efficiency of different structures. Such a procedure, but without the guidance, is included in the ISO 140 standard. More details of this method are given in Chapter 5. The adoption of structural velocity measurements is consistent with the earlier recommendation for measuring room absorption.

Building Facades

Standard procedures for measuring the field transmission loss and noise reduction of building facades are relatively new, and the data base available is too limited for comments to be made on the precision and accuracy. However, a review of the procedures shows a certain degree of internal inconsistency and the potential for inaccuracy, as well as some serious omissions.

First, there is the question as to the type of external sound source to be used in the tests. Both the ISO and draft ASTM procedures allow either traffic noise or a single loudspeaker to be used, but the relationships between measurements performed with the two sources are not available. Certainly, there will be confusion as some people use one method, and others use a different, but allowable, method. Furthermore, the draft ASTM procedure allows the use of traffic noise as a source only for a specified highway configuration.

Second, the external sound level can be measured in three different ways in each of the two procedures. Microphones can be placed in contact with the exterior building surface, if it is smooth, at a distance of 2m from the surface, or in the free field of the source when a loudspeaker is used. In order to obtain consistent results, it is necessary to perform carefully controlled tests to develop relationships between measurements taken at these different locations. It is not at all clear, for example, that the sound level measured 2m from the facade is sufficiently deterministic to be suitable for all conditions.

Third, the measurement of field transmission loss requires a definition of the facade area to normalize the measured level difference. Guidelines need to be given to account for the equivalent area to be used when performing measurements in corner rooms, and for cases when part of the external sound energy is transmitted through the roof. In this context, since protection from external noise is a major consideration for buildings located near airports, it is also necessary to include procedures for measuring the field transmission loss with aircraft as the source of sound.

In summary, it is necessary to develop relationships between the field transmission loss measured using different sound sources and different external microphone locations before the draft ASTM procedure is adopted.

Descriptors For Sound Insulation and Isolation

The review of descriptors for sound insulation and isolation shows that there are many different grading curves either proposed or in use, but that the lack of subjective data makes it difficult to justify any of them. The data that does exist indicates that grading curves and weighted level differences by themselves do not correlate well with subjective reactions. Much better correlation is obtained with a combination of either of these measures of sound isolation with four other quantities. Whether or not this can be reduced to two quantities, as in the proposed Privacy Index, cannot be established without a substantial increase in the data base on subjective response.

The data base used by Schultz[99] in proposing the Privacy Index is limited to only 35 case histories. One of the major uncertainties in developing the correlation between various indices and subjective response lies in categorizing peoples' reactions to noise on some form of scale. Improvements in design criteria cannot be expected until this is done, and the existing data reexamined or additional data is gathered. Meanwhile, Schultz's suggestion that field evaluation should be performed using A-weighted level differences, rather than the more complex NIC rating, is a good one. However, the Privacy Index for design purposes, while intuitively correct, appears to have little advantage over the use of A-weighted level differences, according to the data shown in Reference 99.

Coordination of Efforts

Finally, it should be noted that data on field measurements of transmission loss and noise reduction are largely in the files of acoustical consultants and hence are generally inaccessible. In many European countries, government laboratories have established continuing programs in which a vast quantity of field data have been acquired for a wide range of construction types. These data have been used to:

- Identify and evaluate the effectiveness of current trends in building designs for noise control;

- Identify problem areas where field measured data differ significantly from those measured in the laboratory, and as a result, formulate research programs to provide solutions;
- Provide a means for improving and testing prediction methods and for developing simplified field measurement procedures. As an example, data are required to improve the procedure for predicting the transmission loss of building facade elements exposed to sound incident at certain angles.

In the United States, there is no agency fulfilling the role of a leader in architectural acoustics and building noise control, with the result that there is a lack of coordination and impetus for the promotion of new and existing technology.

5.0 STRUCTURE-BORNE FLANKING TRANSMISSION

5.1 Introduction

It was noted in Chapter 4 that one of the reasons for measured values of field transmission loss being lower than would be expected from laboratory measurements is the presence of structure-borne flanking transmission. The magnitude of such transmission is dependent on the properties of the total building structure and the way in which the various elements are connected. The effect of flanking transmission on the noise reduction between two rooms is also a function of the sound insulating properties of the dividing partition. If the transmission loss of this partition is low, then the sound energy transmitted by flanking paths is usually much less than that transmitted directly through the partition. Thus flanking transmission becomes more important in cases where the sound insulation of the dividing partition is high.

5.2 Factors Influencing Flanking Transmission

An illustration of possible flanking paths between two horizontally adjacent rooms is shown in Figure 26. The sound waves generated by the source excite bending waves in the walls, ceiling, and floor of the source room. These waves are transmitted through the structure and can radiate sound energy into adjacent areas of the building. The ratio of the sound energy transmitted via path A in Figure 26 to the sound energy incident on the partition between the rooms is equal to the transmission coefficient, τ, of the partition, and can be calculated with reasonable accuracy using the procedures summarized in Chapter 2. The energy transmitted via paths B, C, and D is dependent on the properties of the side walls and the partition and their method of attachment. If the transmission via flanking paths B, C, and D combined is small compared to that via path A, the sound isolation between rooms is determined by the transmission loss of the intervening partition. If the transmission via flanking paths is comparable to that via path A, then the sound isolation will be less than the values predicted using the transmission loss of the partition.

An approximate magnitude of flanking transmission in buildings can be determined in terms of the overall performance of the building elements in the following manner. The sound field in the source room excites vibrations in the side walls (assuming that Figure 26

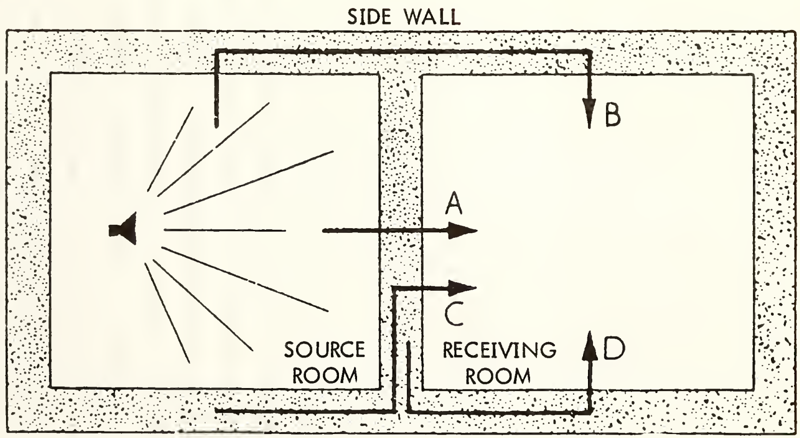

Figure 26. Flanking Paths of Transmission Between Two Rooms.

represents a view looking down on two horizontally adjacent rooms), the transverse velocity of the walls being directly related to their sound transmission loss coefficient.[106] These vibrations propagate along the continuous wall, losing some of their energy at the junction with the partition, and radiate sound energy into the receiving room. The sound energy transmitted via path B is therefore dependent on the following factors:

- The sound level in the source room;
- The airborne transmission loss of the side wall (TL_s);
- The propagation losses in the side walls (T_l);
- The losses occurring at junctions or corners (T_j);
- The radiation factor of the side wall.

Since we are interested only in the sound insulation between the two rooms, it is convenient to normalize the sound level in the receiving room resulting from flanking transmission to the sound level in the source room, and to call the inverse of this ratio the "flanking transmission coefficient" τ_f. The flanking transmission loss TL_f is then equal to $-10 \log \tau_f$. If the areas of the side walls in the source and receiving rooms are S_s and S_r, respectively, then the flanking transmission loss can be expressed as[106]

$$TL_f = TL_s + T_l + T_j + 10 \log \left(\sigma_{forced}/\sigma_{free}\right) + 10 \log (S_s/S_r) \qquad (20)$$

where σ_{forced} and σ_{free} are the radiation factors of the side wall for forced and free bending waves, respectively. This expression only accounts for sound energy transmitted via path B. Similar expressions can be developed for the other paths of transmission, and for radiation from the other surfaces of the receiving room.

The expression given in Equation (20) shows the importance of the factor σ for the flanking wall in determining the flanking transmission loss. The forced bending waves excited in the wall by the sound field in the source room propagate as free waves past the junction with the partition. The radiation factor for free waves is frequency dependent, having a value in the range 0.01 to 0.1 at frequencies less than the critical frequency, increasing to unity at higher frequencies, as shown in Figure 27.[107] The radiation factor for forced waves is also approximately unity above the critical frequency, but does not decrease significantly at lower frequencies. Thus the factor $10 \log (\sigma_{forced}/\sigma_{free})$ in Equation (20) decreases rapidly as frequency increases up to the critical frequency, and assumes the

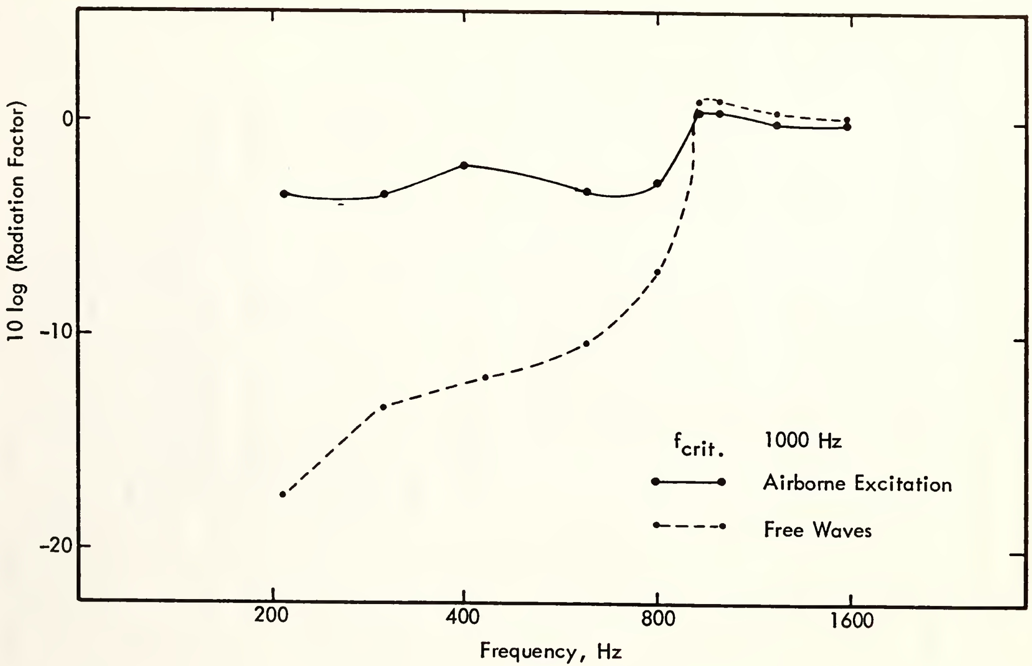

Figure 27. Radiation From Aluminum Plate.[107]

value zero at higher frequencies. On this basis alone, it is evident that flanking transmission can be high if the critical frequency of the flanking structure is low, as in the case for concrete and masonry walls. Opposing this trend, however, is the fact that the airborne transmission loss TL_s is generally high for such massive structures with low critical frequency. For any given frequency, there is actually a range of mass or thickness for a given wall, above which the flanking transmission increases sharply.

An examination of Equation (20) shows that if (as is usual) the propagation loss T_l in the wall is low compared to losses at the junctions, the flanking transmission loss TL_f for path B in Figure 26 at frequencies greater than the critical frequency is given by the approximate expression

$$TL_f \approx TL_s + T_j \tag{21}$$

for the case where the side walls in the source and receiving rooms are identical in size. This simplified expression is applicable to massive structural elements of concrete or masonry exhibiting low values of the critical frequency.

With this simple expression, we can make some rough estimations of the effect of flanking transmission on the sound insulation between two rooms. Using the room arrangement shown in Figure 26, transmission along path B causes sound to be radiated from the two side walls plus the ceiling and floor. We will assume that this radiating area is three times the area of the intervening partition, since not all the four surfaces will normally contribute equally to the radiated sound field. Under this condition, and at frequencies greater than the critical frequency, the reduction in sound insulation due to the presence of the flanking transmission is shown in Figure 28 as a function of the difference in airborne transmission loss for the partition and side walls $TL_p - TL_s$. This figure shows, as mentioned earlier, that the degradation in sound insulation increases as the value of $(TL_p - TL_s)$ increases. If $TL_p - TL_s = 0$, which is the case when the partition is identical to the side walls, a junction loss of at least 10 dB is required for flanking to be insignificant. If $TL_p - TL_s$ is in the range 5 to 10 dB, such as might be the case for the construction tested by Jones[70] (see Figure 24), a junction loss of 15 to 20 dB would be required. Even though these simple calculations do not apply directly to frequencies less than the critical frequency, the general trend is the same for all structures. Positive values of $(TL_p - TL_s)$

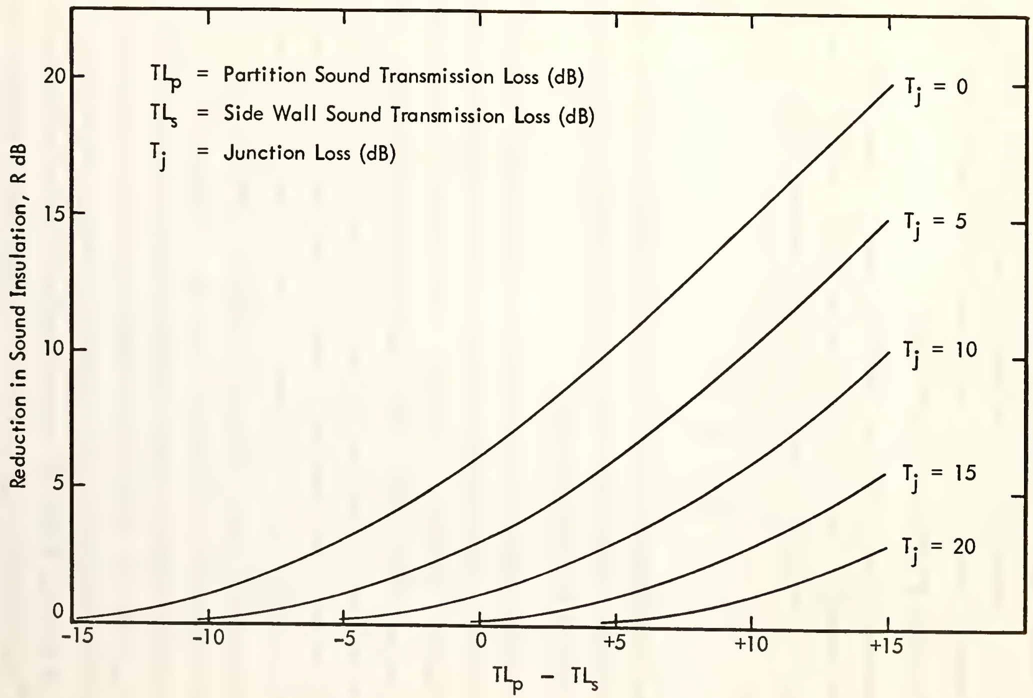

Figure 28. Reduction in Sound Insulation Due to Flanking Transmission.

can be found in buildings with party walls supported on lightweight concrete or wooden floors, and for continuous lightweight concrete walls with floors incorporating resiliently mounted ceilings.

5.3 Theoretical Developments

There have been many attempts to establish theoretical relationships describing the effects of flanking in structures with application to buildings. The more important studies are briefly reviewed in this section.

The propagation of structure-borne sound in structures has been treated in detail by Cremer[11] using classical wave theory applied to infinite plates with corners and junctions. Although the radiation of sound occurs primarily from bending waves, Cremer found that it was also necessary to include longitudinal waves in the formulation since there is some degree of transformation from one wave type to another at corners and junctions. The insulating effect of elastic layers inserted in plates and at corners is shown to occur at high frequencies, with an accompanying maximum transmission at a low-frequency resonance. Although experimental verification of the theory was not performed, it is stated that the results agree qualitatively with measured data for reinforced concrete structures.

Kihlman[108] also uses classical bending wave theory in developing expressions for the transmission of energy at rigid structural junctions. The theory is valid at all frequencies for propagation of free bending waves. For forced waves excited by airborne excitation, the results are valid only at frequencies greater than the critical frequency. Kihlman derives expressions for the energy transmission coefficients at a junction consisting of four semi-infinite plates (see Figure 29) with no internal damping in a similar manner to that employed by Cremer, considering bending, longitudinal, and transverse waves. These coefficients are averaged over all angles of incidence assuming a diffuse two-dimensional field. The advances in digital computers since the time of Cremer's initial work allowed Kihlman to compute numerically values of the transmission coefficient as a function of the plate parameters for concrete and lightweight concrete structures. The transmission of energy along a continuous structure (i.e., from plate 1 to plate 3) at a cross-junction of four structures was found to increase with increasing frequency. However, the transmission around the corner (i.e., from plate 1 to plate 2) at a junction was found to be independent

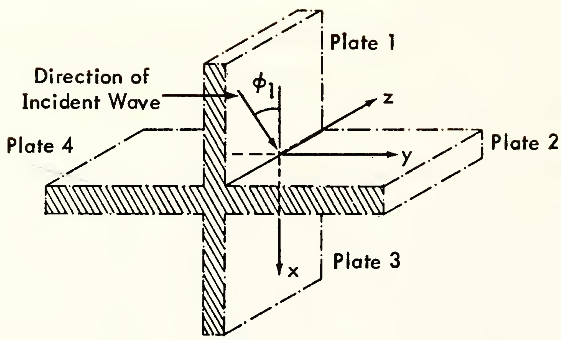

Figure 29. Cross-Junction Arrangement.

of frequency. For the transmission of bending waves along a lightweight concrete structure via a cross-junction consisting of a concrete slab, there is one angle at which the majority of the incident energy is transmitted. This is shown in the curve labelled τ_{13} in Figure 30. The transmission coefficient τ_{12} around a corner of a cross-junction is also shown in this figure. If longitudinal and transverse waves were omitted from the formulation, τ_{13} would exhibit the same function of angle as τ_{12}. Kihlman's computations clearly show the importance of including these other wave types in predicting the transmission through junctions, but they are not required for transmission around corners at junctions. The results indicate that transverse displacements of the junction are much more important than rotation in determining the transmission coefficient. Furthermore, rather large changes in the elastic properties of concrete are required to decrease significantly the transmission of energy at junctions.

Kihlman's theory for semi-infinite plates is applied to finite structures using an energy flow approach, resulting in expressions for the velocity of each of the connected panels. Laboratory experiments showed that the theory agreed reasonably well (generally within 5 dB) with measurements for vibrational excitation of concrete junctions over the frequency range 200 Hz to 3150 Hz — see Figure 31. However, as expected from the assumptions made in developing the theory, the agreement for airborne excitation was good only above the critical frequency. The experiments demonstrated the importance of including longitudinal and transverse waves in the theoretical formulation. Further tests illustrated that significant decreases in transmission can be obtained by using sandwich structures with an inner shear layer providing an overall structure that exhibits higher values of critical frequency than single homogeneous structures of the same mass.

Similar agreement between theory and measurements was found in field tests conducted in buildings with different combinations of concrete elements — see Figure 32. Thus it would seem reasonable to assume that junctions in concrete buildings do in fact consist of rigidly connected panels. However, since edge losses in buildings can be considerable, it is possible to use the simpler infinite panel theory. Only in one case was poor agreement found, this being in the transmission of free waves (excited by a vibrator) from a concrete slab floor to a lightweight concrete wall. In this case, the

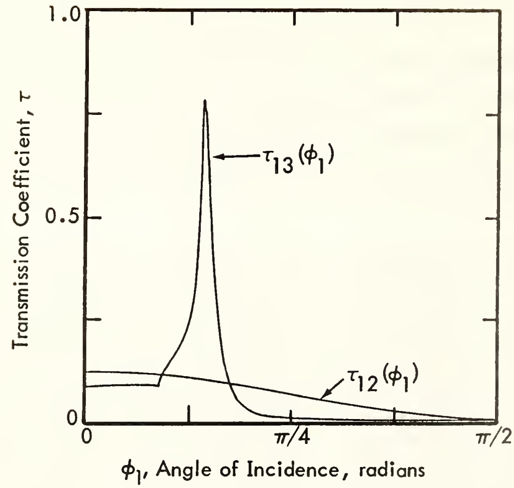

Figure 30. Computed Transmission Coefficients τ as Functions of the Angle of Incidence For 0.15m Concrete Panels at 1000 Hz.[108]

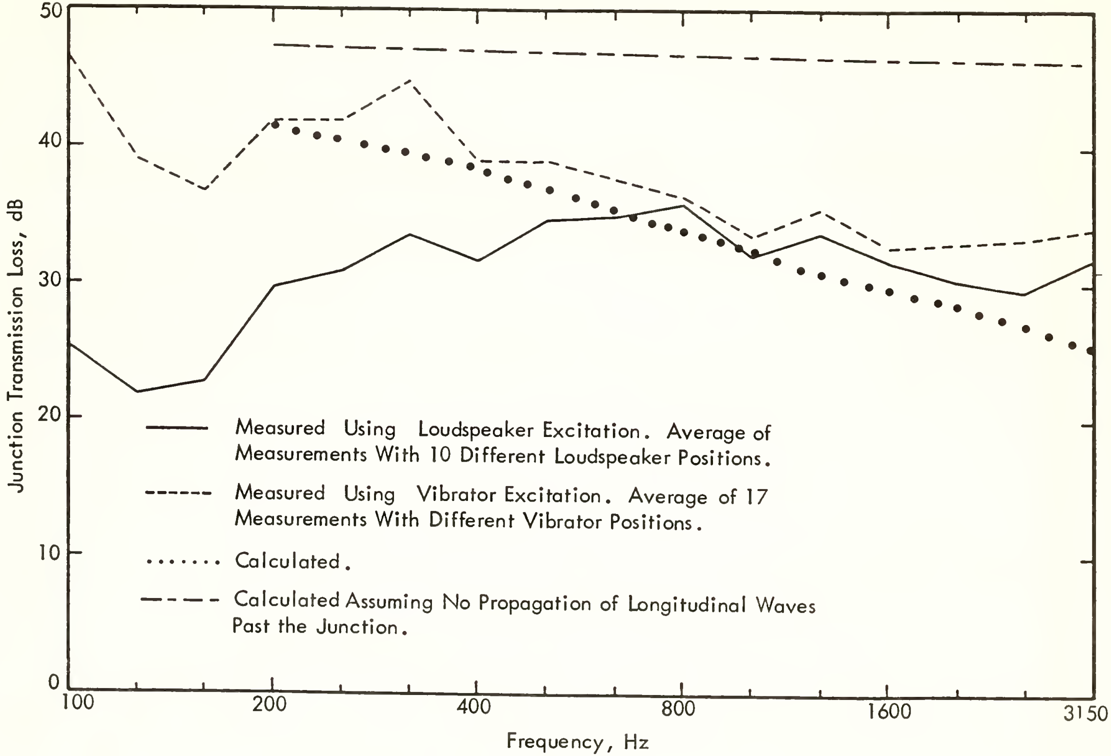

Figure 31. Measured and Calculated Transmission Loss Through a Cross-Junction of Concrete Panels.[108]

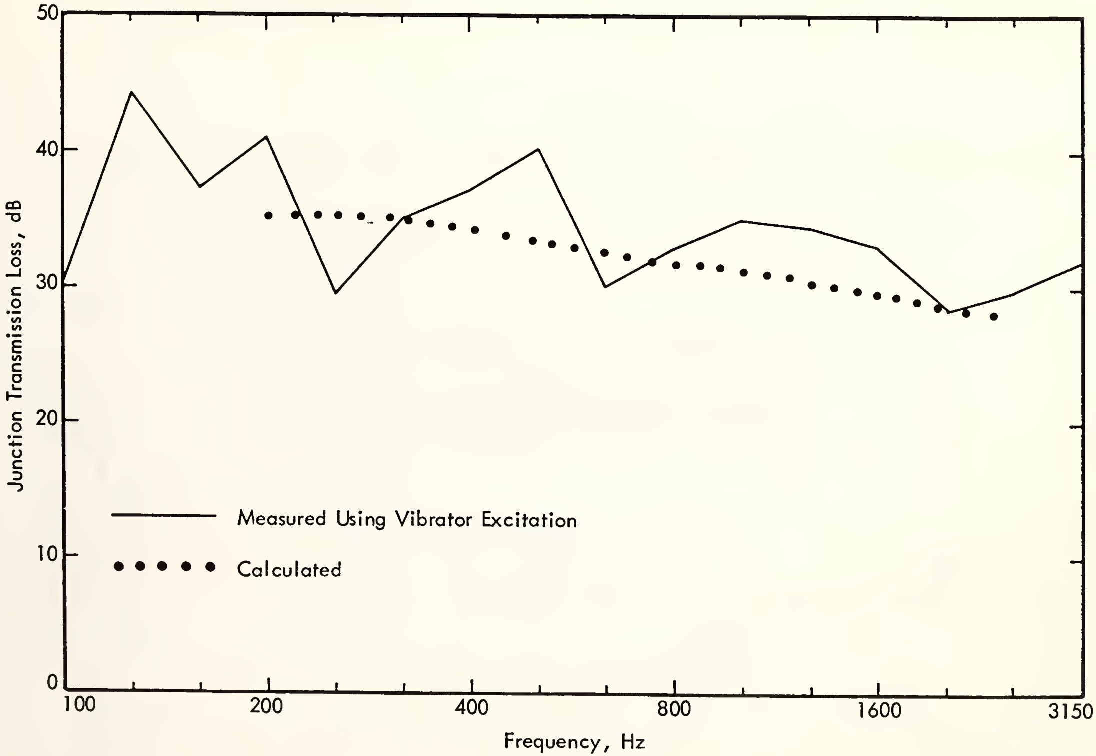

Figure 32. Measured and Calculated Values of Transmission Loss for a Concrete Cross-Junction in a Building.[108]

theory predicted values that were consistently high by about 6 dB, due largely to unusually strong propagation of longitudinal and transverse waves in the thick concrete slab. No explanation of this discrepancy is provided.

Kihlman's work concentrates on propagation through a cross-junction, with only passing reference to "T" junctions. However, a preliminary analysis of a "T" junction using results derived by Cremer showed that high transmission of bending wave energy is possible under certain conditions of incident angle and frequency. Accordingly, Kihlman claims that flanking transmission along outer walls can be higher than for cross-junctions of the same structural elements used as interior walls.

Whereas Kihlman considered only the propagation of structure-borne sound past junctions (T_j), Zabarov[84] extended the theory to include radiation of sound from flanking structures and calculates the flanking transmission loss between rooms. In his theory, Zabarov assumes semi-infinite panels, rigid connections at junctions, and a structure radiation factor of unity. Accordingly, the results are valid only at frequencies greater than the critical frequency. For the concrete panels considered, this validity extends over most of the frequency range of interest in building acoustics.

The transmission coefficients used by Zabarov for corners and junctions are taken directly from the work of Budrin and Nikiforov.[109] The expressions used are for normal incidence bending and longitudinal waves in semi-infinite plates. No experimental validation is given in Reference 109. The frequency dependence of the transmission coefficients is similar to that determined by Kihlman. Furthermore, Zabarov also found that it is necessary to consider bending waves only for the transmission around corners at junctions, but that longitudinal waves must be considered for transmission along the continuous structures through junctions. However, Zabarov goes on to state that connections between floors and walls are filled partly with elastic materials and mortar, allowing some deviation from the assumed rigid connections and reducing the transmission of energy. This, he explains, is the reason for the calculated transmission, including the effect of longitudinal waves, being greater than that measured in the field. On the basis of this practical evidence, the calculations are performed using the simpler equations involving bending waves only. This appears to be in contradiction with Kihlman's findings. Nevertheless, laboratory experiments performed on a scale model gave excellent agreement between measurement and theory. Similarly, good agreement was also found in field tests except at low frequencies — see Figure 33.

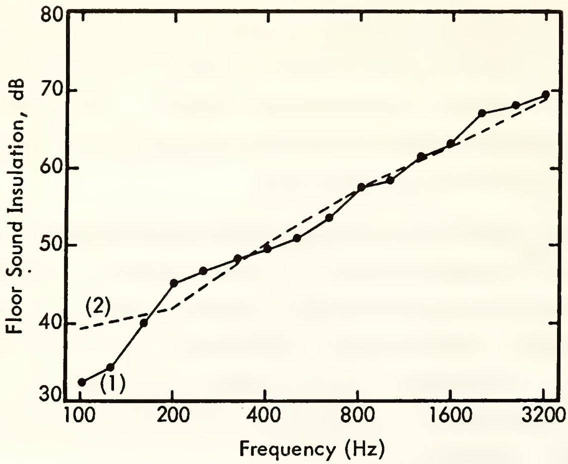

Figure 33. Floor Sound Insulation in a Building. (1) Sound Insulation Measured For a Floor Structure With a Wooden Floor and Suspended Ceiling With Indirect Paths of Noise Transmission; (2) The Same as in (1) But Calculated.[84]

The energy flow approach for calculating propagation losses in connected structures was first developed for aircraft applications, where the riveting or welding of panels to ribs ensures a rigid connection at corners and junctions. Lyon and Eichler[110] have developed expressions for losses at junctions between plates using the energy flow method considering bending waves only and assuming diffuse wave fields in the plates. The agreement between theory and measurement is considered satisfactory only for engineering estimates of transmission at junctions between the steel plates.

Gibbs and Gilford[111] have applied the energy flow method for calculating the sound transmission between rooms in a building, including both direct and flanking paths. They present calculated data showing that the transmission of bending waves through a simple "T" junction can be quite accurately determined without considering longitudinal and transverse waves. It is stated that these waves only need to be included when propagation is over long distances and several junctions. This is in agreement with Zabarov's assumptions. Nevertheless, both types of waves are included in the formulation which uses impedance expressions derived by Kihlman and Cremer for cross-junctions and corners. The calculations of bending wave transmission across a cross-junction exhibit a maximum value approaching unity at an incident angle that is dependent on frequency, similar to Kihlman's results. Averaging over the incident angle, there is fair agreement between theory and measurement for laboratory experiments on cross-junctions at medium and high frequencies — see Figure 34. At low frequencies, the authors explain the poor agreement is due to the low modal density in the individual plates, rendering the energy flow approach invalid.

Measurements of bending wave transmission conducted in two model rooms with one connecting edge showed only reasonable agreement between theory and measurement when one of the walls was excited by a vibrator. However, the measured and predicted difference in sound levels in the two rooms agreed quite well.

In summary, it appears that the basic theory for the propagation of structure-borne sound is well established for single homogeneous panels. The application of classical bending wave theory and energy flow analysis provides values for the transmission coefficient of corners and junctions that are in reasonable agreement with measured results obtained from laboratory experiments. However, the agreement holds only at frequencies greater than the critical frequency for airborne excitation. Thus the theory is applicable

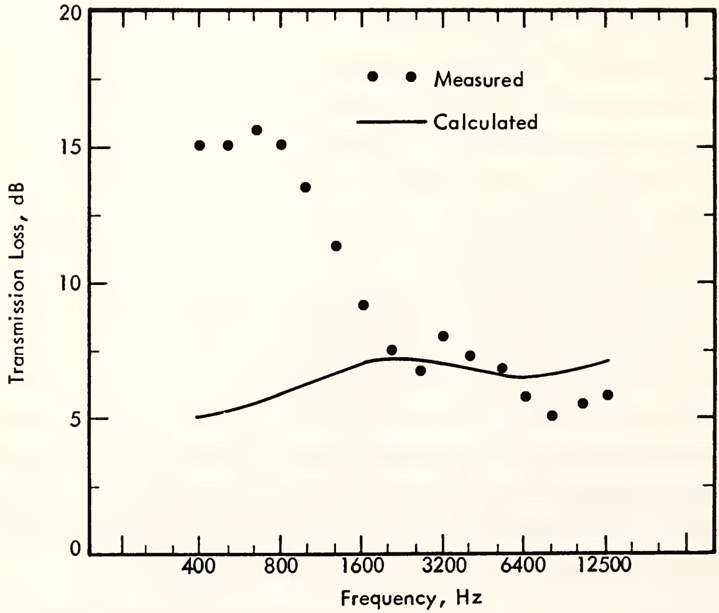

Figure 34. Measured and Calculated Values of Transmission Loss At a "T" Junction.[111]

to the more massive building structures, such as concrete and masonry. Furthermore, the modal density of plates at low frequencies is generally too low for the energy flow approach to be valid, unless the calculation bandwidth is increased. When applied to building structures with high energy losses at the edges, it is acceptable to use the infinite plate theory.

In calculating the bending wave transmission coefficients for cross-junctions, it is necessary to include longitudinal and transverse waves for transmission through the junction. For transmission at right angles and around corners, it is only necessary to consider bending waves. When the theory is applied to buildings, however, the imperfect connections (which may be elastic) between elements may eliminate the need for including wave types other than bending. In this context, there appears to be some discrepancy in the literature as to the rigidity of the connections between concrete plates in buildings.

It should be noted that, in general, validation of the basic theory has been limited to measurements of plate velocities on both sides of junctions and corners. In only a few cases has the theory been applied to the calculation of noise levels in adjacent rooms with flanking paths. At frequencies greater than the critical frequency, where the radiation factor for plates is unity, the extension to calculating noise levels is trivial and reasonably accurate. At lower frequencies, the low modal density and the uncertainty in estimating plate radiation efficiency (other than by direct measurement — see Section 5.4.4) can lead to significant disagreement between theory and measurement of noise levels.

The fact that the theories are not applicable for airborne excitation in the frequency region below the critical frequency may be important for lightweight structures with low bending stiffness. For these structures, flanking transmission can only be determined at the higher frequencies. Below the critical frequency, the propagation velocity for forced waves caused by airborne excitation is greater than for free waves, with the result that the transmission coefficients for corners and junctions is different to that predicted by the theories discussed in this section. However, the importance of structure-borne wave propagation in this frequency range in determining the flanking transmission loss between two adjacent rooms may be minimized because the radiation factor for free waves decreases below the critical frequency.

In reviewing the state-of-the-art for flanking transmission theory, it is apparent that there is a lack of prediction methods available for wood-frame structures. The effect

of wood-frame motion in a double-panel wall has been treated by Fahy[33] in predicting the airborne transmission loss, but the effects of junctions in wave propagation was not considered. There are various statements in the literature that frame walls couple well at junctions resulting in a higher transmission of energy by flanking paths. However, wood-frame wall structures commonly used in the United States generally have at least one of the walls of gypsumboard or a similar material with a high critical frequency. Accordingly, flanking should not be a serious problem at low and medium frequencies, unless the direct airborne transmission loss of the separating partition is high. On the other hand, the critical frequency of concrete/wood and wooden floors is much lower, so that significant flanking transmission is sometimes observed.

5.4 Measurement of Flanking Transmission

There are numerous examples of field measurements in the published literature illustrating the effect of flanking transmission in reducing the airborne sound insulation between rooms in buildings. This section describes some of the methods that have been used to quantify the flanking transmission loss and identify the major paths of sound propagation, and discusses their application to diagnostic evaluations of building structures.

5.4.1 Comparison With Laboratory Data

The most commonly used method for identifying flanking transmission is to compare values of transmission loss of partitions measured in the field with those measured in the laboratory under controlled conditions. This method has several drawbacks. First, measurements conducted in the laboratory cannot be considered absolute since the methods of construction and mounting together with differences between laboratory facilities can lead to considerable uncertainty in the "true" transmission loss of a partition (see Chapter 3).

Second, it has been noted by Jones[70] that field measurements of transmission loss can be affected to a significant extent by the absorption characteristics and sound diffusion in the source and receiving rooms. Whereas the presence of flanking paths can reduce the sound isolation between rooms, an increase in room absorption can increase the measured sound insulation of the intervening partition. Jones concludes that one effect can cancel the other, with the result that the real magnitude of flanking transmission is unknown. For

example, a difference of 3 STC points was noted in the transmission loss of a wood-frame partition measured in the laboratory and in the field with bare source and receiving rooms. When carpets and drapes were added to the rooms there was no difference between laboratory and field measurements.

Third, it is necessary to ensure that all air leaks are sealed and other airborne flanking paths are eliminated to estimate the extent of structure-borne flanking paths. Of course, the major airborne paths of transmission should be sealed in a well-constructed building. However, it may be necessary to seal all potential airborne paths to determine the upper limit of sound insulation imposed by structure-borne flanking. With these considerations, it is apparent that a comparison of laboratory and field data can only be used as an approximate screening method for identifying serious cases of flanking transmission.

5.4.2 The ASTM Procedure

The standard test procedure for measuring airborne sound insulation in buildings, ASTM E336-77,[86] includes a flanking test that must be used in determining the field transmission loss of a partition. The test involves a standard measurement of sound insulation followed by a similar measurement with the application of a temporary shield to the test partition. If the difference in the two measured values of sound insulation is at least 3 dB, then it is assumed that no significant flanking exists. With a properly designed and installed shield, this method, although cumbersome and time consuming, will correctly identify significant flanking in most cases. It is possible, however, that measurement errors, particularly at low and medium frequencies in small rooms, could lead to an incorrect decision in cases where flanking transmission is high. Furthermore, the method does not identify the specific flanking paths that limit the sound isolation between rooms. The ASTM test procedure suggests a method for identifying flanking paths by adding shields to the walls, ceiling, and floor of the receiving room. This method is so time consuming as to be impractical in most situations.

5.4.3 The Vibration Simulation Method

A method for measuring the direct and flanking contributions to the sound field in a room has been proposed by Meyer, etal.,[112] using vibrators to excite bending waves in the surfaces of the adjacent source room. The level of excitation is adjusted to provide the

same surface velocity distribution in the receiving room as measured with airborne excitation of the structure from the adjoining source room. Then, by selective excitation of the surfaces and the partition, the radiated sound energy contributions from each path in Figure 26 can be determined and the flanking transmission via each surface identified.

Meyer found that relatively few vibrators were required to simulate the bending wave patterns in the room surfaces, provided that a high accuracy was not required. The reproducibility of the measured vibration levels for different vibrator locations was about the same as for airborne excitation. However, the complexity of the method renders it suitable only for research purposes, or for the design and development of techniques for reducing flanking transmission.

5.4.4 The Sound Power Method

The sound power radiated by a vibrating surface is proportional to the product of the mean square velocity of the surface and its radiation factor. At frequencies greater than the critical frequency, the radiation factor for free bending waves is unity. Therefore, in this frequency range, the sound power radiated by each surface of a room adjoining a source room can be calculated from measurements of the surface velocity. For accurate results at low frequencies, several velocity measurements must be taken at different positions on the room surfaces. This method has been used extensively and is capable of providing accurate results — see Figure 35.[113] The advantage over many other methods is that flanking contributions from each surface can be identified.

At frequencies lower than the critical frequency, the radiation factor for free waves is much less than unity and is a complicated function of the panel damping, the panel dimensions, and the method of mounting. Therefore, to use the sound power method, it is first necessary to measure the radiation factor. Alternatively, the sound power radiated by a panel can be measured directly. Madacam[114,115] has conducted experiments to measure radiated sound power by suitably processing the outputs from a closely spaced accelerometer and microphone. The total radiated sound power is determined by averaging the data over a number of measurement locations. Using this method, Macadam showed that the calculated and measured sound levels in a room are in good agreement — see Figure 36.

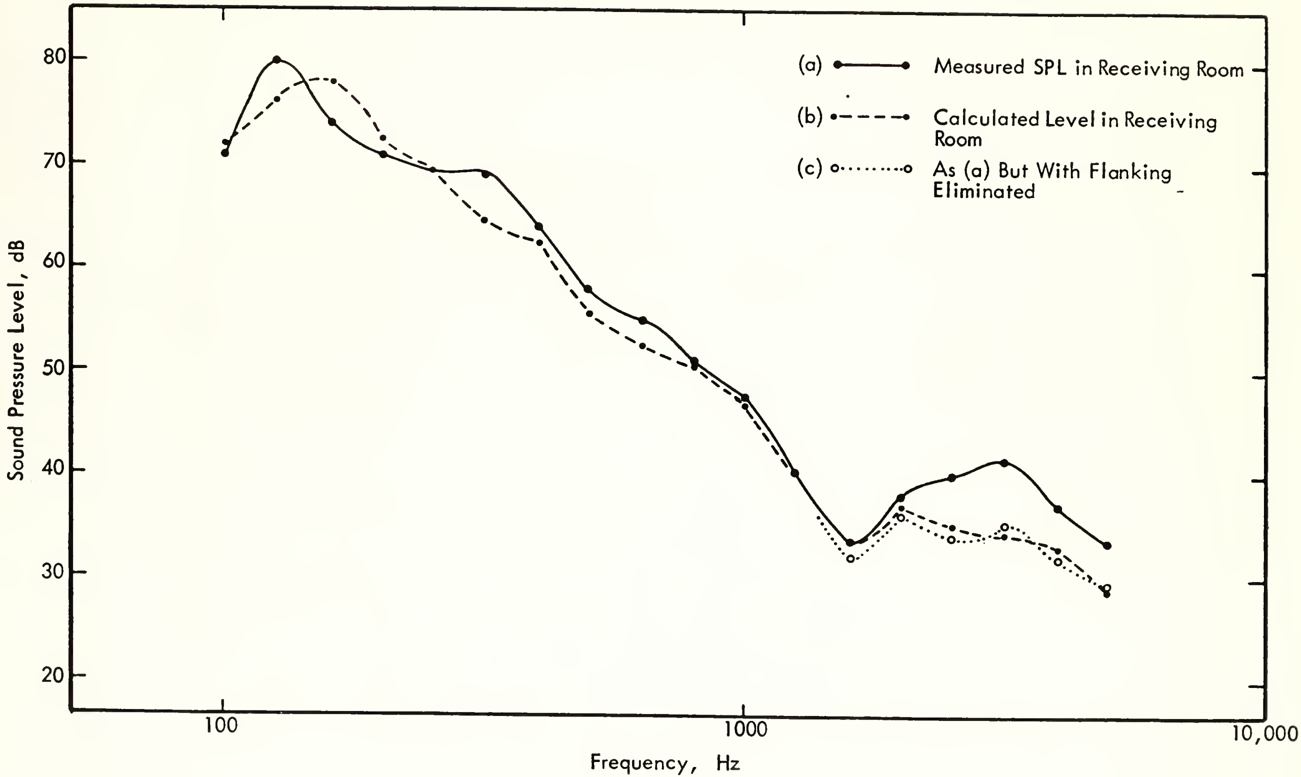

Figure 35. Sound Pressure Level in Receiving Room Showing The Effects of Eliminating Flanking.[113]

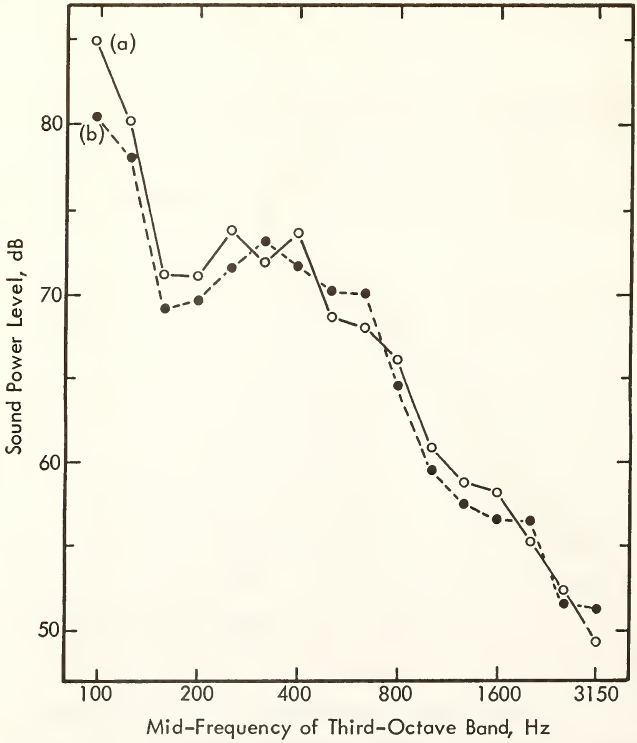

Figure 36. The Total Sound Power Radiated Into The Receiving Room In The First Sound Transmission Experiment: (a) By Independent Method; (b) By Direct Method.[114]

5.4.5 The Correlation Method

The strength of individual contributions from flanking paths of transmission can also be determined by performing a cross-correlation between the acoustic signals in the source and receiving rooms.[116,117,118] Using a random noise source, the acoustic signals received by microphones in each room are delayed in time with respect to each other, multiplied together, and integrated over a given time that is long compared to the period of the lowest frequency of interest. The resulting cross-correlation function, when plotted as a function of delay time, can be used to separate and identify the arrival of contributions from each airborne or structure-borne flanking path.

In the identification of flanking paths by the cross-correlation method, it is not necessary to measure the sound level in the source room — the electrical input to the sound source can be correlated with the acoustic signal from the microphone in the receiving room, and a correction applied for the frequency response of the source. This effectively eliminates the multiple reflections that would be picked up by a microphone in the source room, and provides a much smoother correlation function. Good agreement has been obtained between one-third octave band measurements and the correlation technique for determining the increase in sound levels due to flanking paths.[116]

In some respects, this method is similar to the short-pulse method proposed by Raes,[119] in which a short tone burst is produced in the source room and the amplitudes of the direct and flanking contributions are separated directly in time on an oscilloscope. In both cases, the time delay between the direct and flanking signals can be varied by moving the source and microphone to identify the location of flanking paths. Both methods are suitable for identifying airborne flanking transmission paths, but difficulties may be encountered in identifying specific structure-borne flanking paths. Furthermore, both methods involve only single angles of incidence from the source to the partition separating the two rooms and to the flanking structures, which further complicates the analysis of the results.[120] Of the two, the pulse method is simpler to perform and involves less complicated instrumentation. However, with further development, particularly with regard to understanding the results obtained, and the increasing availability of compact instrumentation, the correlation technique could be a useful tool for field diagnostic measurements.

5.4.6 Summary of Measurement Methods

Several methods have been devised or adapted to quantify flanking transmission in buildings. Some of these — namely, the vibration simulation and correlation methods — are too complex to be used for field diagnostic work, but may be valuable for R&D studies. As a screening tool to identify serious cases of flanking transmission, measured data can be compared to laboratory results. In fact, such a comparison should always be made to verify the overall design of the building. This leaves two methods which are available for identifying specific paths of flanking transmission, namely, the ASTM procedure and the sound power method.

The ASTM procedure is currently only required in the measurement of field sound transmission loss. It is a cumbersome method that may not always provide the correct answers, unless shields are added to each room surface. However, with the additional shields, it is a workable method that does not require any additional instrumentation or training beyond that required for field sound insulation measurements.

The sound power method using an accelerometer only can be applied successfully to structures such as concrete or masonry which have low values of the critical frequency. It is not complex, requires only one additional piece of instrumentation, and can be conducted quickly with reasonable accuracy. For lightweight structures, and particularly wood-frame structures, it is necessary to know the radiation factor to make accurate diagnostic measurements.

5.5 Summary and Recommendations

A review of the literature shows that cases of structure-borne flanking that degrade the sound insulation in buildings are common. The magnitude of the degradation depends on the properties of the structural elements and the way in which they are connected. In Europe, considerable work has been conducted in an attempt to understand the mechanisms of flanking transmission, with particular application to high-rise buildings constructed of lightweight concrete. As a result of this work, building codes in many European countries include a requirement on propagation losses at junctions to minimize flanking transmission. Although the problem has been acknowledged in the United States, little work has been conducted on typical building structures. The cost of overdesign or of modifying the

structure after construction can be considerable. However, the cost of incorporating measures to reduce flanking in the design stage may be relatively low. At present, there are minimal guidelines for use in the design of such measures.

The basic theory for propagation of structure-bome sound has been well established by the work of Cremer[11] and Kihlman.[108] However, because of the interest in lightweight concrete structures in post-war Europe, it is largely restricted to vibrational excitation of structures at frequencies greater than the critical frequency. Moreover, few attempts have been made to apply the theory to frame walls which are common in the United States. To extend the theory, it is necessary to include the radiation factor for various structural types. Theoretical expressions are available, but it may be more convenient to perform a series of measurements of the radiation factor for different structures and attempt to collapse the data into a few typical categories. The theories should then be simplified for use in the design process — something that was not done by previous workers — and the attenuation characteristics of different materials and different joints included.

The lack of a simple procedure for routinely measuring structure-borne flanking transmission has severely limited quantitative diagnosis of problems in finshed, or partly finished, buildings. The current ASTM procedure is just too cumbersome for this purpose. The measurement of wall and floor velocities can be a valid technique if information on radiation factors is available. It is recommended that the results obtained from the expansion of the theory – see above – be used to develop a simple method for assessing the relative contribution of the radiation from each room element to the total sound level.

Although data exist to indicate the presence of significant structure-borne flanking transmission in some buildings, the extent of the problem is not well documented, largely because flanking has not been separated from other factors degrading the performances of structures in the field. It is recommended that the program for gathering field data described in Chapter 4 also include measurements of flanking transmission. The data would be used to identify particular building types with flanking problems that would then be the subject of research programs.

6.0 ENERGY CONSIDERATIONS

6.1 Introduction

In recent years the cost of energy, in particular that generated from petroleum products, has increased dramatically, and forecasts indicate that this trend will continue for the foreseeable future. Rising energy costs have significantly increased the operating costs in residential and commercial buildings, where a major portion of the energy, 51 percent and 39 percent, respectively, is used for heating.[121] It has been postulated[122] that "without a great deal of increased discomfort or cost to the owner, it is technically possible to reduce the heating energy consumption of an average house at least 50 percent." If the same technology were applied to commercial building space heating, the implementation of a conservation program could reduce energy costs by many billions of dollars and substantially reduce the dependence on scarce natural resources. This type of energy conservation has, in fact, been accepted as official U.S. policy with the passage of the National Energy Conservation Act of 1978.

It has been noted that a certain degree of synergy exists between energy conservation in buildings and methods for protecting occupants from exterior noise. By applying the proper noise control technology, it is possible in some cases to achieve energy conservation. The success of this approach to obtain mutual benefits depends on the ability to understand the similarities and differences between methods for achieving energy conservation and noise control in residential and commercial buildings.

6.2 Mechanisms of Heat Loss in Buildings

There are two fundamental mechanisms by which heat energy is lost from buildings. The first mechanism is air infiltration, the second is the transmission of heat through the building structure.

Heat is lost by air infiltration through the process of convection. Warm inside air escapes to the outside through openings around windows and doors and cracks through the walls, floors, and ceilings. As the warm air escapes, it is replaced with colder outside air which must then be heated and possibly moisturized. It is the energy used to heat and moisturize this new air that is considered wasted and can be saved through proper conservation methods.

In high-rise buildings, air is transferred from the lower floors to the higher floors by convection. As the warm air rises, cold outside air is drawn into the lower level of the building to replace it; the rate at which this takes place is proportional to the height of the building.

The exchange of the air inside a building with fresh outside air is a natural and necessary process. It is necessary in order to rid the building of air which has a high density of carbon dioxide, to clear the air of contaminants such as smoke from cigarettes, cooking and heating by-products, dust, etc., in order to make the inside space more comfortable for the inhabitants. Currently, residential buildings in the U.S. have air infiltration rates of one to two air changes per hour. There have, however, been homes built in Canada, Sweden, and the U.S. with air infiltration rates on the order of one-quarter air change per hour. While reducing the air infiltration rate to this low level does indeed lower the energy usage, there are health hazards associated with it which must be taken into account.[121] These problems include increased odors from human activity, increased humidity in the building, and increased chemical contamination such as formaldehyde and Radon produced from the outgassing of the building materials — especially masonry products — i.e., bricks, blocks, etc.

Conduction is the process by which heat is lost by transmission through the building structure, i.e., walls, floors, roof, windows, etc. The amount of heat loss is dependent on the thermal resistance of the specific building material used. The structure acts as a heat sink, absorbing the heat in the air and releasing it to the outside. Energy must then be spent to reheat the inside air. It is this energy that can be saved as a result of a successful energy conservation program.

6.3 Energy Conservation and Sound Insulation

In designing a new building, or in soundproofing an existing building, it is necessary to consider three major paths by which noise can be transmitted. These paths are illustrated in Figure 37, and may be summarized as follows:[123]

- Air infiltration (gaps, cracks, and vents)
- Small wall elements (walls and doors)
- Main wall and roof elements

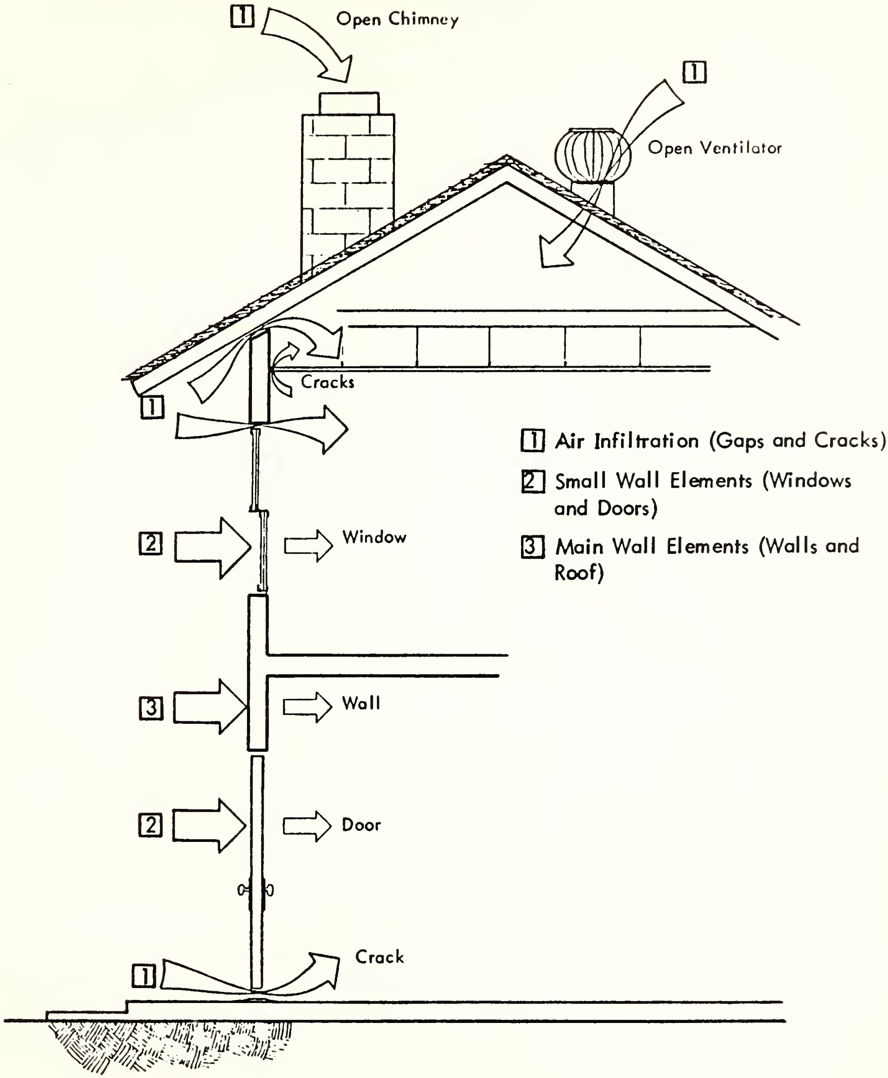

Figure 37. Conceptual Illustration of the Three Major Types of Paths By Which Noise Is Transmitted To Building Interiors.

With all windows and doors closed, the weakest acoustical elements will be gaps, cracks, and vents. Gaps and cracks occur most often in the older houses where the weather-stripping is in poor condition, and where cracks have appeared in the wall near to the window or a door frame. Other paths of entry in this class of acoustical weak links include chimneys without dampers and most types of vents to the exterior, including mail slots. The first step of soundproofing involves closing or sealing these leaks, and providing acoustic baffles for the vents. However, for the building to be habitable, a certain minimum air infiltration is necessary, and this must be provided by an air ventilation system of some kind.

Further reduction in the interior noise level beyond this first step requires more care since the weak acoustical paths are now not so obvious and the effort may be wasted on unnecessary items. In most cases, the next step is to modify the windows and doors themselves which become the dominating paths in terms of noise entry after the gaps and cracks are sealed. A double-window system is required together with a solid core-type door, both of which must include good quality edge seals. The exceptions to these requirements occur on the shielded sides of the building which often require no further treatment beyond the first stage. If a dwelling has a beamed ceiling, then modification of the roof may be necessary, partly on account of the poor attenuation characteristics of beamed ceilings but mainly because of the large area involved. These modifications form the second stage of soundproofing.

The final stage of soundproofing, if the two previous stages do not provide adequate noise reduction, is modification of the main wall and roof elements. Two of the simpler modifications are addition of absorbing material to the ceiling, and resilient mounting of the interior wall panels. For walls with single continuous studs, adding absorption to the cavity increases the transmission loss at low frequencies only. Over most of the frequency range, the transmission occurs through the studs rather than the cavity.

The three stages of soundproofing correspond to the stages of modifying buildings to conserve energy. Table 1 shows the benefits gained at each step and a qualitative estimate of the initial modification costs.[123] The actual costs incurred (in 1978 dollars) in previous soundproofing programs are shown in Figure 38[124] for residential structures[125] and commercial structures.[126] Also included in this figure are data points for schools and hospitals[127] averaged nationwide for different climate conditions. Procedures for determining the initial costs of modifications and savings due to lower energy usage have been published, and used

Table 1

Relative Aspects of Noise Reduction Modifications to External Walls[124]

Noise Reduction Modification	Increase in NR of Structure	Initial Modification Cost	Additional Ventilation Required	Heating and Air Conditioning Energy Savings
SEAL LEAKS Seal all cracks, openings, leaks, with caulk, tape, or weatherstripping around door, window, wall joint seams. Provide acoustical baffles for chimneys, ventilators, etc.	Up to 4 dB	Low	High	High
SMALL ELEMENT MODIFICATION For windows, doors, air conditioners, ventilators, install new elements with upgraded EWNR comparable to that of wall structure.	Up to 10 dB over sealing of cracks; typically, 4 to 7 dB	Moderate	None	Moderate
WALL PANEL MODIFICATION Construction changes to walls, roof, including stud space insulation and resilient mounting of interior surface.	Up to 10 dB over small element modifications; higher for more extensive modifications.	High	None	Moderate

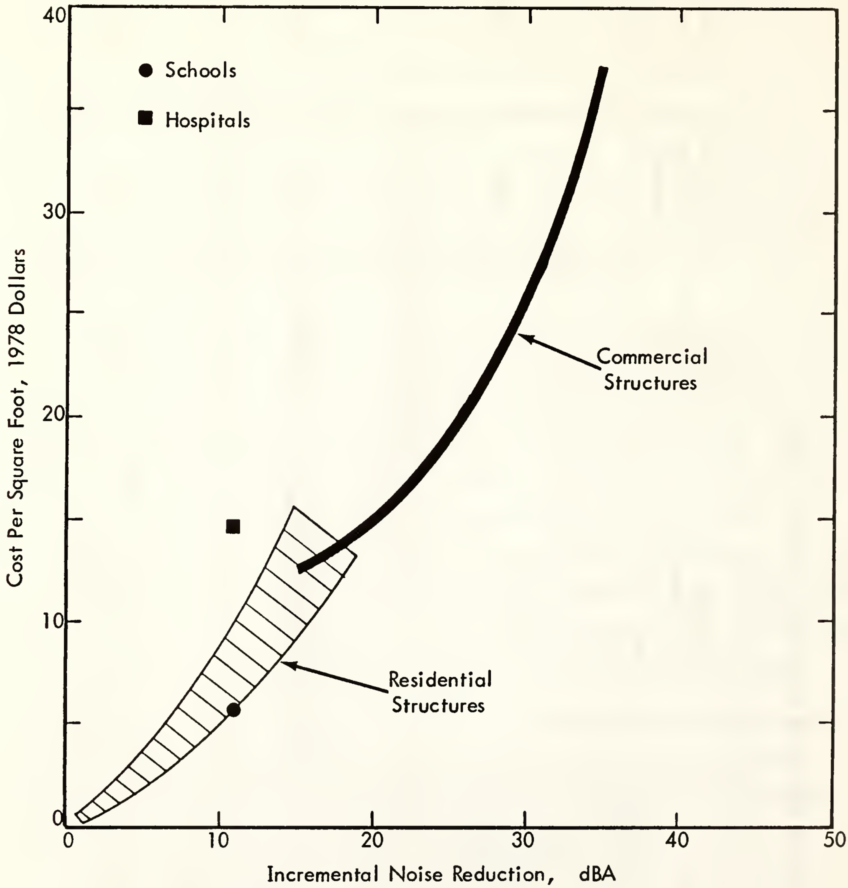

Figure 38. Estimated Costs of Noise Insulation For Residential and Commercial Structures, Adjusted to 1978 Dollars.[124]

to evaluate the benefits of soundproofing public buildings against aircraft noise.[127] It has been estimated that soundproofing schools and hospitals near major airports alone would result in a net energy cost saving of over $36 million (in 1977 dollars) in 10 years. The most striking example of such mutual benefits occurs in the Northeast region of the United States, where the energy savings per school are estimated to be about $6,000 per year. Thus it is apparent that existing methods for soundproofing buildings can result in significant energy savings.

In general, it can be stated that modifications to an existing structure to increase the noise reduction result in decreased energy losses. However, existing common structures providing a high transmission loss are not always the most efficient for energy conservation. For example, whereas a concrete or brick wall exhibits an STC rating 5 to 10 points greater than a standard stucco wall on a wood frame with gypsumboard interior panels, its thermal transmittance is much higher if the latter structure includes absorption in the cavity. Another example can be found in the use of metal resilient mountings, which can increase the transmission loss significantly without affecting the thermal transmittance. A good data base on the thermal transmittance and sound insulating properties of basic building elements that demonstrates this fact is presented in Reference 128.

In Chapter 2 of this report, construction methods were described for reducing the cost of sound insulation. One method is to reduce the transmission of vibration through the studs in double-panel assemblies by inserting a resilient material between the panels and the studs. With absorption in the cavity, the heat flow through the studs in a typical exterior wood-sided wall with cavity absorption is in the range 10 to 20 percent of the heat flow for the complete wall.[128] This could be reduced significantly if the resilient material was also a heat insulator, such as plastic foam or rubber. Heat flow through panel connections may also be important in double-window assemblies with metal frames. The transmission loss of double windows is certainly improved by reducing vibrational transmission via this path. Therefore research aimed at improving the transmission loss of double-panel constructions by modifying connections between the panels will provide energy benefits as a side result.

It should be noted that the new construction methods described in Chapter 2 rely partly on cavity absorption to achieve their stated values of transmission loss. Single-stud exterior constructions commonly used in existing buildings do not require cavity absorption

for noise control, and benefit acoustically only at low frequencies if it is added. The new constructions therefore provide mutual benefits of increased transmission loss at low cost and reduced heat losses.

The similarity between noise reduction and heat loss has been used to develop a method for identifying paths of heat flow by means of acoustic measurements.[129] The method applies only to energy losses by air infiltration, and involves sound level measurements near potential leaks in external structures with a source of sound inside the building.

In contrast to the synergy that exists between noise reduction and energy conservation, there is little relationship between noise reduction and the fire retardant properties of structures. The fire rating of a structure is the period of time that the structure can resist a standard fire exposure before exhibiting certain critical characteristics. It is normally expressed in integral time periods, i.e., 1 hour, 2 hours, etc., and for typical interior building partitions, lies within the range from 1 to 3 hours. With such a course rating scheme covering the wide range of STC values available from interior partitions, it is therefore not surprising that there is a low correlation between fire rating and sound insulation. In fact, the STC rating for different partitions can vary by up to 10 dB for the same fire rating.

6.4 Ventilation Requirements

As noted in the previous section, air leakage paths are the controlling factor for both sound insulation and energy conservation in buildings. Attempts to achieve benefits in either area by structural modifications are wasted if air leakage paths are not first treated. The noise reduction provided by the building shell can be increased by up to 4 dB, and possibly more in old buildings, at a relatively low cost, so the benefit/cost ratio of eliminating air leakage paths is high. However, once air leaks are sealed, ventilation must be provided by other means in order to preserve the interior air quality. In warm or humid climates, air conditioning may also be required, and energy must be expended to move and condition the air. As a result, the benefit/cost ratio of sealing leaks is often decreased.

Natural ventilation can be provided without compromising the sound insulation of the building shell by installing baffled vents of the type shown in Figure 39.[130] Alternatively, the vent can be built into the wall itself, as shown in Figure 40.[130] If necessary, additional air circulation can be achieved by installing a small fan in the baffled duct. Several different

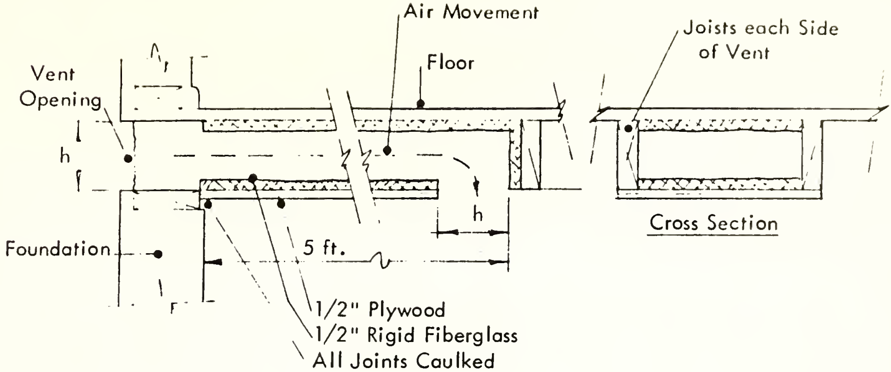

Figure 39. Under-Floor Vent.[130]

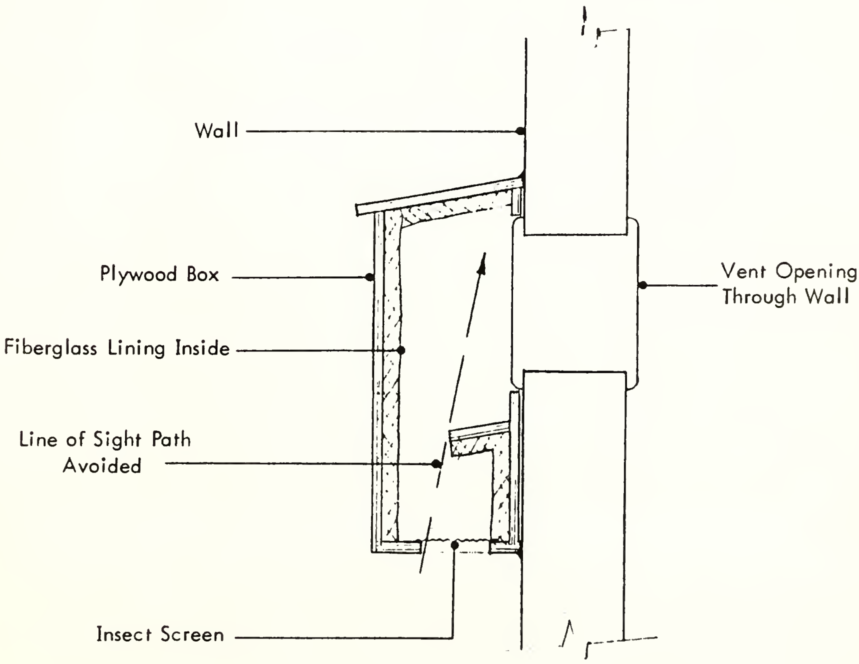

Figure 40. Side Wall Baffled Vent.[130]

versions of such vents for different applications have been designed and shown to be suitable for protection against high exterior noise levels.[130] They are particularly effective for under-floor areas, and attics. A flow-through system can significantly lower attic temperatures and reduce the energy needed to cool dwellings in the summer months. In some cases, cases, the need for cooling may be eliminated with a combination of natural ventilation and a flow-through attic system.

The use of artificial ventilation systems to provide the needed air changes in residential buildings modified to reduce interior noise levels from nearby highways has been successfully demonstrated in England by the Building Research Establishment.[131] A simple mechanical ventilator unit, as shown in Figure 41, was used in conjunction with a permanent exhaust vent, shown in Figure 42. Both systems were provided with lined ducts to reduce the transmission of sound. The fans, operating against the backpressure introduced by the ducts, generated interior A-weighted sound levels of 40 dB or less. The results of this demonstration formed the basis of the United Kingdom Noise Insulation Regulations,[132] which provide for the noise insulation of residential buildings exposed to increased external noise from new or modified highways.

In the warmer climates, air conditioning is required to provide a satisfactory environment in the summer months. Reducing air infiltration for sound insulation purposes will reduce the cooling load required. It is still necessary to introduce fresh air and exhaust stale air, but this can be done more effectively through controlled vents than by air leaks distributed about the building. In the dry climatic regions of the country, it is possible to use the old type of evaporative air conditioners that use considerably less energy to operate than the common electrical systems. In humid regions, air conditioning is often used more as a dehumidifier than as a method for cooling the interior air. Where temperatures are moderate, commercially available dehumidifiers can be used alone, thus reducing the energy consumption.

The noise reduction provided by a building shell can be increased by introducing balconies or shields outside windows facing major sources of noise. By the careful use of absorption, May has shown that interior noise levels can be reduced by 5 to 10 dB.[133] Balconies also serve to reduce solar heating in the summer, while allowing this additional and free type of heating in the cooler months. The sliding glass doors often associated with balconies

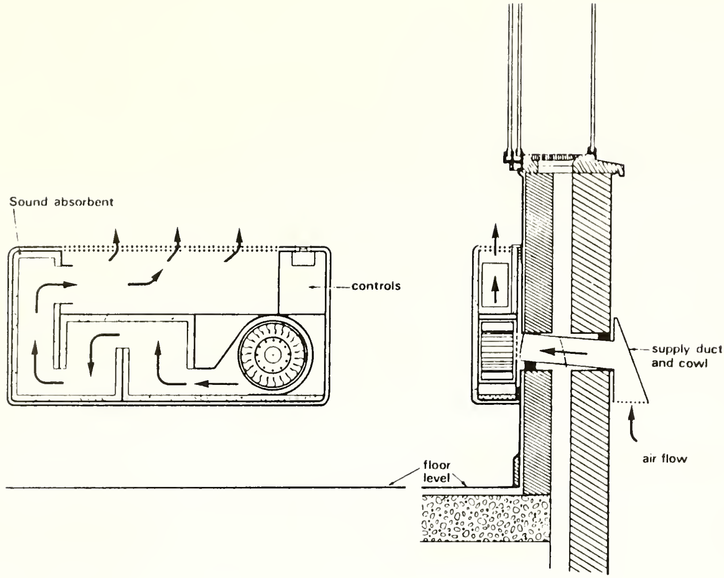

Figure 41. Mechanical Ventilation Unit With Sound-Attenuating Labyrinth.[131]

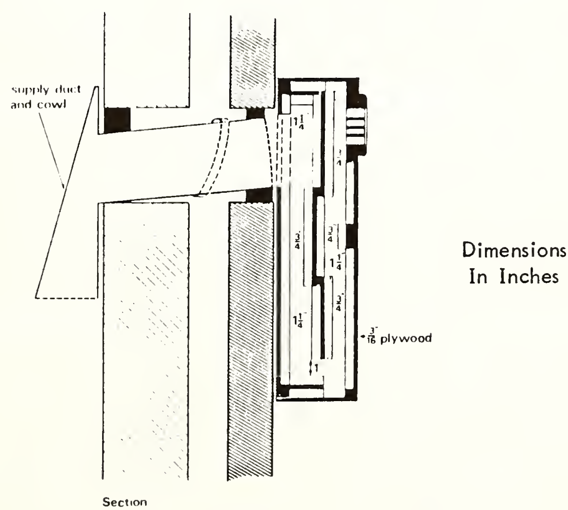

Figure 42. Permanent Side Wall Exhaust Vent.[131]

present a major problem in building noise reduction because of their large surface area, relatively low transmission loss, and extensive perimeter leaks. The latter can be minimized by careful design and maintenance, but increases in the transmission loss can only be achieved by installing double-glazing, either in the existing frames or as a separate structure.[130]

The major use of energy in the home and in commercial buildings is for heating. Increasing the sound insulation of the building shell by eliminating air infiltration paths will therefore cut down on heating costs considerably. Again, fresh air can be introduced in a controlled way through one or two baffled vents. Innovations such as heat exchangers can be used to preheat the incoming air using the heat collected from the exhausted air.

6.5 Summary and Recommendations

A review of energy considerations in buildings shows that modifications of structural elements to increase the sound insulation generally reduces energy losses. However, sound insulation alone is not always a good indicator of energy efficiency. The steps involved in soundproofing a building against exterior noise are the same as those for reducing energy losses — namely, first to eliminate air leaks, second to modify windows and doors, and third to modify the main structural elements. The technology for these modifications is known and has been successfully demonstrated.[125] Therefore a national program to soundproof buildings in high noise areas would be expected to reduce operating costs and conserve scarce natural resources.

New types of construction, discussed in Chapter 2, designed for increasing the benefit/cost ratio for sound insulation, also offer potential savings in energy over existing structures, although this has not been demonstrated experimentally. Further work is required to design resilient mounting methods for double-panel assemblies that reduce thermal transmission through the connecting studs and metal window frames.

The literature[37] contains methods for predicting the transmission loss of double-panel constructions, and these can be used to optimize designs for low cost, weight, or thickness. Methods are also available for predicting the sound insulation provided by a combination of building elements.[128] The thermal transmittance of each element can be estimated using well-established methods, provided that the transmittance of the components of each element are known.[123,128] A valuable tool for building design would consist of a combination of

these prediction procedures, enabling the designer to optimize for both sound insulation and energy conservation, and to evaluate trade-offs between the two.

Sealing the air leaks in a building increases sound insulation and reduces energy losses. However, fresh air must be introduced into the building and stale air exhausted. The required air changes can be controlled effectively by means of single vents, baffled to reduce sound transmission, and equipped with heat exchangers to reduce heat losses. Mechanical ventilation systems have been shown to be effective in building noise control, and are used extensively in the United Kingdom. Simple calculations indicate a significant savings in operating costs, if air conditioning is not required, which can offset the initial costs of modification to a considerable degree. It would be a simple and useful exercise to perform similar cost estimates for typical buildings in different climatic regions of the United States.

National programs for noise abatement have generally addressed the source of noise, often the most cost-effective means of reducing community noise exposure, but one that involves long lead times for the benefits to be achieved. The Department of Housing and Urban Development does include noise reduction requirements for federally funded development loans, and the Federal Highway Administration is currently conducting demonstration projects to evaluate soundproofing as a means for reducing the exposure to noise from federally funded highways. Also, the Federal Aviation Administration has studied the feasibility of soundproofing public buildings near airports. However, there have been few studies of the benefits and costs of a national soundproofing program for residential buildings. Soundproofing by itself is not suitable for residential houses in very high noise areas, because the exterior noise levels are too high, but it is suitable for apartment buildings in these areas, and for residences exposed to lower noise levels. It is recommended that soundproofing buildings be given more emphasis in national and local noise abatement programs, particularly in view of the potential benefits in reduced energy consumption.

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☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This report presents a critical review of the status of technology in sound transmission through building structures, and identifies specific areas for further research. The approach taken in the review follows the steps involved in the design process, namely, prediction, measurement, and evaluation. Priorities for further research are based on the potential for achieving the following objectives:

- To develop new technology to reduce the cost of noise control in buildings;
- To increase confidence that designs will provide the required acoustical privacy; and
- To identify and apply sound isolation techniques that reduce energy consumption.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Acoustics; building acoustics; noise control; noise isolation; sound transmission; structure-borne noise.

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